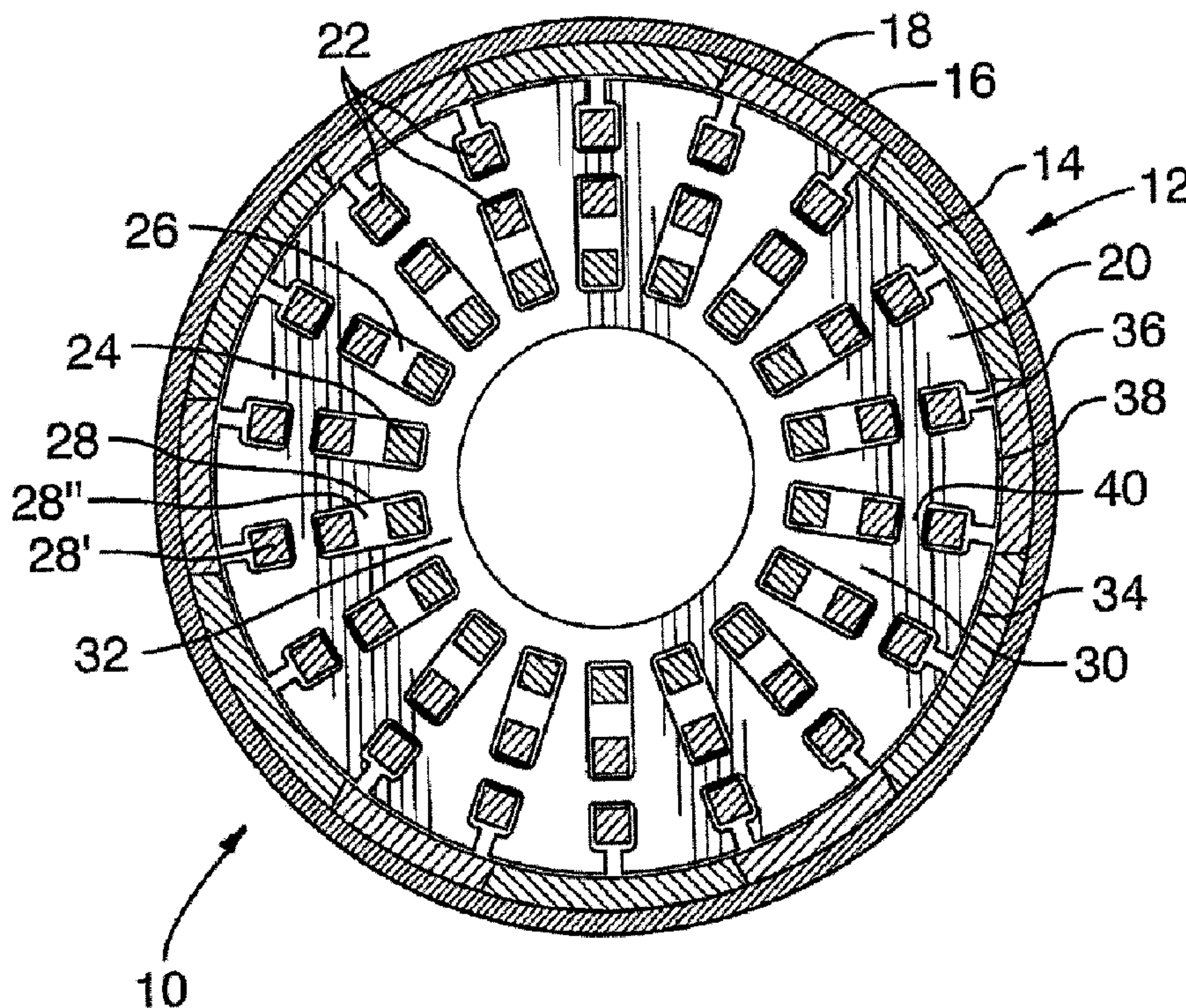




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(57) **Abrégé/Abstract:**

The invention includes an electric machine (10) having a rotor (12), stator (20) and at least one winding (22) in the stator (20) adapted to conduct a current, and a secondary winding (24), electrically isolated from the first winding (22) and inductively coupled to the first winding (22), which may be used to control at least one of the output voltage and current of the first winding (22).



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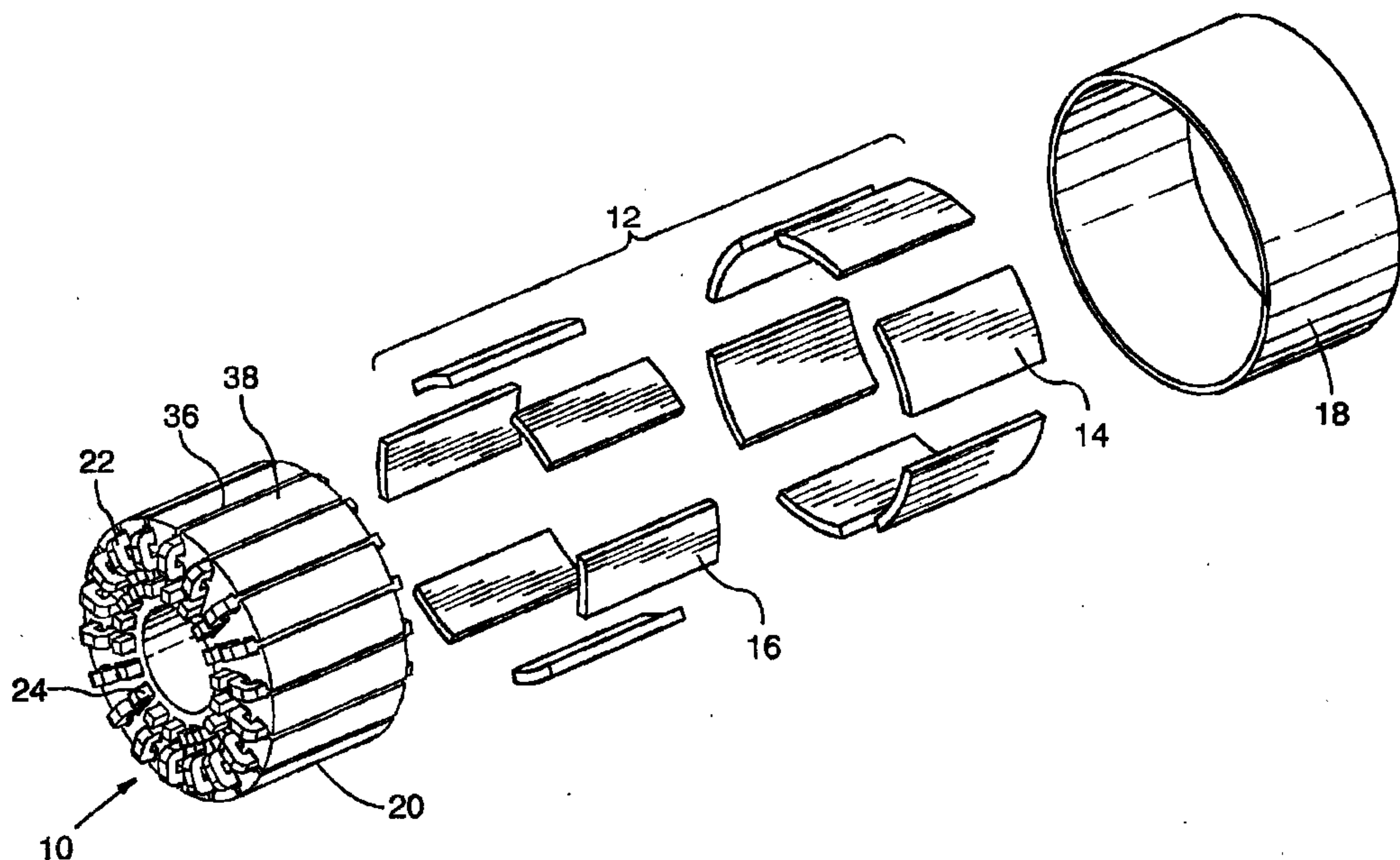
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(57) Abstract: The invention includes an electric machine (10) having a rotor (12), stator (20) and at least one winding (22) in the stator (20) adapted to conduct a current, and a secondary winding (24), electrically isolated from the first winding (22) and inductively coupled to the first winding (22), which may be used to control at least one of the output voltage and current of the first winding (22).

WO 2004/107540 A1

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ELECTRIC MACHINE

**Technical Field**

5 [0001] The invention relates to electric machines such as alternators and motors and, more particularly, to a novel architecture for such machines.

**Background Of The Art**

10 [0002] Referring to Figure 1, a typical permanent magnet (PM) machine according to the prior art is shown at 100. Prior art PM machine 100 has a rotor 102, with permanent magnets 104 mounted thereto by a retaining ring 106, which is mounted on a rotatable shaft 108. Rotor 102 is adjacent a stator 110 having a plurality of windings 112 interspersed between a plurality of teeth 114 mounted to a back iron 116. (For ease of illustration, the adjacent elements of windings 112 in Figure 1b are shown unconnected.) As is well understood, PM machine 100 may operate in a generator/alternator mode or a motor mode. When operated in a generator/alternator mode, an external torque source forces rotation of the shaft (and thus the rotor and the magnets), and the interaction of the magnets and the windings causes a magnetic flux to loop the windings in the slots. As the rotor rotates, the magnetic flux in the stator structure changes, and this changing flux results in generation of voltage in the windings, which results in an output current that can be used to power electrical devices, or be stored for later use. When operated in a motor mode, a voltage from an external source is applied to the stator windings which causes current flow in the windings and results in a magnetic flux to be set up in the magnetic circuit formed by the teeth and back iron. When current is supplied in an appropriate manner to the windings, the rotor can be made to rotate and thus produce usable torque. The operation of such machines is thus well understood.

30

[0003] Such PM machines can have an "inside rotor" configuration as shown in Figures 1a and 1b, or an "outside rotor" configuration as shown in Figures 2a and 2b. The reference numerals in Figures 2a and 2b correspond to the corresponding features described with reference to Figures 1a and 1b.

In the "outside rotor" configuration, however, rotor yoke 108' replaces rotor shaft 108. For ease of illustration, the adjacent elements of the windings in Figure 2b are also shown unconnected.

5 [0004] Irrespective of whether operated in an alternator or motor mode, the magnetic flux path in these prior art PM machines is as partially and simply depicted in Figure 3, the flux path as indicated by the arrows 118, and the poles and virtual poles denoted by an "N" or an "S". It is this magnetic flux 118 which induces a voltage in the alternator winding 112 (or in the case of a  
10 motor, creates the magnetic attraction with the permanent magnet 106 to cause rotor rotation), as described above.

[0005] Prior art PM machines (and particularly PM alternators) suffer from at least two limitations which has limited their usefulness somewhat, namely:  
15 (1) the output of the PM alternator may only be controlled within the machine (i.e. varied) by varying the rotor speed (assuming a fixed geometry machine), and (2) if a short circuit or other internal fault occurs in the machine, the internal fault current can become extremely destructive to the machine, particularly in high power applications. With reference to the first drawback,  
20 this intrinsic feature particularly limits the usefulness of a PM generator in circumstances where the rotor rotation speed cannot be independently controlled. It would therefore be desirable to improve the controllability of PM machines, generally.

25 [0006] PM machines offer certain attractive advantages for use in high speed applications, and particularly as an integrated starter-generator (ISG) for a propulsive or prime-mover gas turbine engine, in which the PM machine is mounted directly to a turbine shaft of the engine. This shaft, of course, is driven at whatever speed is required for the running of the gas turbine engine  
30 (typically anywhere in the range of 0 - 50,000 rpm) and thus the shaft speed cannot be varied to suit the controllability limitations of the PM machine, but rather is dictated by the mechanical output requirements of the engine. Therefore, although the ISG designer will know the average steady state speed of the turbine shaft at cruise, can thus design an PM alternator system

to provide sufficient electrical output necessary to power the aircraft systems at cruise (where the engine typically spends most of its operation cycle), accommodations must be made for take-off (where the turbine shaft may be turning at twice cruise speed, doubling alternator output) and landing  
5 approach (where turbine shaft speed may half of cruise speed, halving alternator output). The problem is an order of magnitude greater for certain military applications, where cruise speed is rarely maintained for any length of time. The prior art therefore poses optimization problems to the ISG designer, where critical over-power and under-power scenarios must be managed to  
10 achieve a satisfactory design.

**[0007]** There are other drawbacks inherent prior art designs, which result in complicated mechanisms and fabrication techniques. U.S. Patent No. 6,525,504 to Nygren et al. shows one example of a relatively complicated  
15 solution to the control of certain aspects of the operation of a PM machine used in high voltage power generator applications. The device offers only limited control over operation of the machine, and its complexity makes it unsuitable for higher reliability and lighter weight applications such as, for example, aircraft applications.

20

**[0008]** Accordingly, there is a need to provide an improved PM machine which addresses these and other limitations of the prior art, and it is an object of this invention to do so.

## 25 **Summary of the Invention**

**[0009]** In one aspect, the present invention provides an electric machine operable as an alternator, the machine comprising a magnetic rotor mounted for rotation about an axis; a stator adjacent the rotor, the stator including a plurality of radial slots defined in the stator between pairs of teeth, and a  
30 bridge mounted to the stator in at least one of the slots and extending between a pair of said teeth defining the at least one slot, the bridge dividing the at least one slot into at least two slot portions; a first winding forming at least a portion of a first circuit, the first circuit adapted to deliver generated electricity from the machine, the first winding having a loop portion including at

least a first leg and a second leg, the loop portion disposed in the at least one slot such that the first leg is disposed in a first one of said at least two slot portions and adjacent a first side of the bridge, and the second leg is disposed in a second of said at least two slot portions and adjacent a second side of the bridge, the first and second sides of the bridge opposing one another; and a second winding forming at least a portion of a second circuit, the second circuit electrically isolated from the first circuit, the second winding disposed in the stator adjacent the second leg of the first winding.

10 [00010] In another aspect, the invention provides an electric machine operable as an alternator, the machine comprising: a rotatable magnetic rotor; and a stator assembly mounted adjacent the rotor assembly, the stator assembly including a plurality of openings including a first opening and a second opening, the first and second openings being separated by a portion  
15 of the stator assembly, a first electrical winding electrically connected to a first circuit, the first circuit adapted to provide electricity output from the machine when the machine is operated as an alternator, the first electrical winding disposed at least partially in the first opening and at least partially in the second opening so as to at least partially form a loop, and a second electrical  
20 winding connected to a second circuit, the second electrical winding electrically isolated from the first electrical winding, the second winding disposed in the second opening adjacent the first winding, wherein said portion of the stator assembly defines a portion of at least two magnetic circuit paths in the stator assembly for guiding magnetic flux generated as a result of  
25 the rotor rotating about the stator, and wherein a first one of said at least two magnetic circuit paths at least partially encircles the first opening and first winding therein, and wherein a second one of said at least two magnetic circuits at least partially encircles the second opening and the first and second windings therein, and wherein the secondary magnetic circuit is defined  
30 entirely within the stator assembly.

[00011] In another aspect, the invention provides a machine operable as an alternator, the machine comprising: a rotatable rotor; at least a first winding electrically connected to a machine output adapted to deliver generated

output electricity from the machine when the machine is operated as an alternator; at least a second winding including a current-limiting device, the second winding electrically isolated from the first; and a stator adjacent the rotor, the stator defining at least a first opening and a second opening, the first winding disposed in the first opening and second opening, the second winding disposed only in the second opening, the stator and rotor together defining a primary magnetic circuit path around the first opening, whereby relative movement between the rotor and the stator causes a primary magnetic flux to flow around the primary magnetic circuit path which thereby induces a voltage across the first winding and an associated current flow in the first winding, the stator also defining a secondary magnetic circuit within the stator around the second opening, the first and second windings being disposed in the first and second openings and the first and second openings being positioned in the stator such that, in use, said voltage and current induced in the first winding induces a secondary voltage and an associated current flow in the second winding, wherein the current-limiting device is adapted to prevent a current flow in the secondary winding when a pre-selected threshold current in the secondary winding is exceeded, the second winding thereby limiting a maximum current flow in the first winding to at least a desired maximum current flow limit.

**[00012]** In another aspect, the invention provides a machine operable as an alternator, the machine comprising: a rotor having a plurality of magnetic poles; a first winding electrically connected to a machine output, the output adapted to deliver generated output electricity from the machine; a second winding including a current-limiting device; and a stator adjacent the rotor, the first and second windings disposed in the stator, the stator and rotor together defining a first magnetic circuit around a portion of the first winding, the stator defining a second magnetic circuit within the stator around a portion of the first and second windings, wherein the first and second windings are inductively coupled such that, in use, a voltage and current induced in the first winding by rotation of the rotor induces a secondary voltage and a current flow in the second winding, and wherein when a pre-selected threshold current is exceeded in the second winding, the current-limiting device prevents current

flowing through the secondary winding, thereby limiting a maximum current flow in the first winding.

**[00013]** In another aspect, the invention provides a permanent magnet machine operable as an alternator, the machine comprising: a rotor having a plurality of permanent magnetic poles; a stator adjacent the rotor, the stator including at least a first winding disposed in at least one slot in the stator and a transformer disposed in the stator, the first winding inductively coupled to the rotor such that rotation of the rotor induces an output voltage and current in the first winding, the transformer electrically connected to the first winding and adapted to control at least one of said output voltage and current of the first winding.

**[00014]** In another aspect, the invention provides an electric machine operable as an alternator, the machine comprising: a stator; a magnetic rotor opposing the stator; and at least two windings disposed in the stator and electrically isolated from one another, wherein a first of the at least two windings comprises a primary winding in the stator for at least one of producing and consuming power, and wherein rotation of the rotor induces an output voltage and current in the primary winding, and wherein a second of the at least two windings comprises a secondary winding in the stator, the secondary winding being arranged and disposed in the stator adjacent a portion of the primary winding such that said induced current in the primary winding induces at least a voltage across the secondary winding, and wherein the secondary winding is inductively coupled substantially only to the primary winding and is inductively isolated from the rotor, and wherein the electric machine further includes means for controlling current flow in the secondary winding, said means adapted to thereby affect current flow in the primary winding.

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**[00015]** In another aspect, the invention provides an electric machine operable as an alternator, the machine comprising: a rotor having a plurality of magnetic poles; a stator adjacent the rotor, the stator having an electromagnetic core portion defining a plurality of radially extending teeth, at



least one bridge portion extending between two adjacent teeth, a first winding wound around the core and wound around the at least one bridge portion, and a second winding electrically isolated from the first winding and disposed in the stator adjacent the first winding, the second winding wrapped around the core portion but disposed remote from the bridge portion.

**[00016]** In another aspect, the invention provides a method of controlling an alternator, the alternator having a stator having at least one core portion extending between a plurality of radial teeth, , a first winding wound around the at least one core portion and a second winding adjacent a portion of the first winding, the first and second windings electrically isolated from one another, the method comprising the steps of rotating the rotor to induce primary current, the primary current thereby inducing a secondary current in the second winding, and controlling the current flow in the second winding to thereby limit the maximum current in the first winding.

**[00017]** In another aspect, the invention provides a method of controlling a permanent magnet alternator, the alternator having a rotor, stator and at least one winding in the stator adapted to conduct an output current induced in the winding by rotation of the rotor, the method comprising the steps of: providing secondary winding electrically isolated from the at least one winding; placing the secondary winding adjacent a portion of the at least one winding; inductively coupling the secondary winding to the at least one winding and inductively isolating the secondary winding from the rotor, such that in use the at least one winding induces at least a voltage in the secondary winding; and using the secondary winding to control at least one of the voltage and current of the at least one winding.

**[00018]** Still other inventions are disclosed in this specification and attached figures, as well.

#### **Brief Description of the Drawings**

**[00019]** For a better understanding of the present invention and to show more clearly how it may be carried into effect, reference will now be made by

way of example to the accompanying drawings, showing articles made according to preferred embodiments of the present invention, in which:

- 5 [00020] Figure 1a is a cross-sectional view of a typical permanent magnet (PM) machine according to the prior art;
- [00021] Figure 1b is an exploded isometric view of the prior art device of Figure 1a;
- 10 [00022] Figure 2a is a cross-sectional view of a typical PM machine according to the prior art having an "outside rotor" configuration;
- [00023] Figure 2b is an exploded isometric view of the prior art device of Figure 2a;
- 15 [00024] Figure 3 is a cross-sectional view similar to Figure 1a, schematically showing magnetic flux paths;
- [00025] Figure 4a is a cross-sectional view of a PM machine according to the present invention;
- 20 [00026] Figure 4b is an exploded isometric view of the device of Figure 4a;
- [00027] Figure 4c is a rear isometric view of a portion (i.e. a few adjacent loops) of the primary winding of the device of Figure 4a;
- 25 [00028] Figure 4d is an isometric view of the secondary winding of the device of Figure 4a;
- 30 [00029] Figure 4e is an enlarged isometric view of a portion of the rotor and stator of the device of Figure 4a, with a portion broken away to reveal detail therein and schematically showing some magnetic flux paths in the device;

[00030] Figure 5a is an exploded isometric view of a second embodiment of a PM machine according to the present invention, with the stator shown in ghost lines to reveal the winding detail therein;

5 [00031] Figure 5b is an enlarged isometric view of a portion of the stator of the device of Figure 5a, with a portion broken away to reveal detail therein;

[00032] Figure 5c is an enlarged cross-sectional partial view of the device of Figure 5a, schematically showing magnetic flux paths in the device;

10

[00033] Figure 6a is an exploded isometric view of a third embodiment of a PM machine according to the present invention;

15 [00034] Figure 6b is an isometric view of the stator of the device of Figure 6a;

[00035] Figure 6c is a rear isometric view of the stator of Figure 6b;

20 [00036] Figure 6d is an enlarged isometric view of a portion of the rotor and stator of the device of Figure 6a, with a portion broken away to reveal detail therein;

[00037] Figure 6e is a partial cross-sectional view of the portion of the rotor and stator shown in Figure 6d;

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[00038] Figure 6f is a cross-sectional view along the lines *6f-6f* in Figure 6e;

30 [00039] Figure 7a is an isometric schematic representation of a method for making primary windings in accordance with the present invention;

[00040] Figure 7b is much-enlarged cross-section of a portion of a stator showing the windings of Figure 7a;

**[00041]** Figure 8a is an enlarged isometric view and a cross-sectional view similar to Figures 6d and 6e, respectively, schematically representing electrical and magnetic activity on start up of the present invention;

5 **[00042]** Figure 8b is an enlarged isometric view and a cross-sectional view similar to Figure 8a, respectively, schematically representing electrical and magnetic activity immediately after the moment in time represented in Figure 8a;

10 **[00043]** Figure 9 is a schematic of an equivalent electrical circuit of one phase the device of Figure 6a;

**[00044]** Figure 10 is a schematic of an embodiment of a secondary winding control circuit;

15

**[00045]** Figure 11a and 11b are schematics of other examples of secondary winding control circuits;

20 **[00046]** Figure 12a is an enlarged isometric view and a cross-sectional view similar to Figures 6d and 6e, respectively, schematically representing electrical and magnetic activity of another embodiment of the present invention employing a low Curie point material;

25 **[00047]** Figure 12b is an enlarged isometric view and a cross-sectional view similar to Figures 6d and 6e, respectively, schematically representing electrical and magnetic activity after the secondary winding fuse of the present invention blows;

30 **[00048]** Figure 13a is an enlarged isometric cross-sectional view of a portion of the stator of another embodiment of the present invention;

**[00049]** Figure 13b is an enlarged isometric cross-sectional view of a portion of the stator of an alternate design for the embodiment of Figure 13a;

[00050] Figure 14 is a schematic of an aircraft accessory system employing a multi-channel version of the present invention; and

[00051] Figure 15 shows a gas turbine engine incorporating the present invention, with a portion of the engine broken away to reveal a cross-section thereof.

#### **Description of the Preferred Embodiments**

[00052] A permanent magnet (PM) machine according to the present invention is depicted in at 10 in Figures 4a to 4f. Referring first to Figures 4a and 4b, PM machine 10 has a rotor 12 which includes a plurality of permanent magnets 14 retained by a yoke 16 and retention sleeve portion 18. Machine 10 also has a stator 20 which includes at least a primary winding 22 and at least a secondary winding 24 (for clarity, only one of each such winding is shown), separated in this embodiment by a winding air gap 26 and disposed in radial slots 28 between a plurality of adjacent teeth 30 in a back iron 32. (For ease of illustration in Figure 4b, the adjacent elements of secondary winding 24 are shown unconnected.) The winding air gap serves as insulation and may be replaced by other suitable insulation. A rotor air gap 34 separates rotor 12 and stator 20 in a typical fashion, and a stator tooth gap 36 separates adjacent teeth 30 at a rotor interface surface 38 of stator 20. Primary winding 22 and secondary winding 24 are thus electrically isolated from one another. Stator 20 also includes a core or "bridge" portion 40 bridging adjacent pairs of teeth 30 and passing between adjacent portions of primary winding 22, as will be described in more detail below.

[00053] The materials for PM machine 10 may be any deemed suitable by the designer. Materials preferred by the inventor are: samarium cobalt permanent magnets, maraging steel (preferably 250 or 300) retention sleeve, aluminum yoke, copper primary and secondary windings, a suitable electromagnetic material for the stator teeth and for the back iron.

[00054] Referring to Figures 4c and 4e, primary winding 22 of the embodiment of Figure 4a consists of a conductor which enters a first end 27

of a slot 28a on a first side 40' of bridge 40, and a first leg portion 23' of winding 22 travels down slot 28a, an end turn portion 23" of winding 22 crosses bridge 40 at the second (i.e. other) end 29 of slot 28a and a second leg portion 23'" travels back along slot 28a and exits slot 28a from the first end  
5 27, but on a second side 40" of bridge 40 (i.e. opposite to the first side 40' the winding entered). Primary winding 22 then continues along the first end 27 of the stator to the next appropriate slot 28b and again enters from the first end 27 of slot 28b, but preferably from the second side 40" of bridge 40 (i.e. the same side of bridge 40 as it exited the last slot 28a). Primary winding 22 then  
10 travels down slot 28b, loops around bridge 40 at the second end 29 of slot 28b, then proceeds back up slot 28b and exits the first end 27 of slot 28b, and is now again on the first side 40' the bridge piece, and so on. Primary winding 22 is thus positioned in the desired slots 28 in stator 20. This particular pattern both facilitates assembly (as will be discussed further below) and  
15 provides an orderly arrangement for primary winding 22, and also beneficially assists winding separation within PM machine 10 (see Figure 7b).

[00055] Referring to Figure 4d, secondary winding 24 in the embodiment of Figures 4a-4f is a shorted winding to provide a squirrel cage configuration.  
20 Secondary winding 24 thus has a plurality of legs 42 extending between end rings 44.

[00056] Referring to Figure 4e, a close-up partial isometric section shows the relative arrangements of primary winding 22 and secondary winding 24  
25 (only a portion of one primary winding 22 is shown for clarity). In operation, as will be described in greater detail below, the interaction of magnets 14 and windings 22, and windings 22 and 24, creates magnetic flux within PM machine 10. Referring to Figure 4e, a primary magnetic flux path or magnetic circuit 46 and a secondary magnetic flux path or magnet circuit 48 are set up  
30 within PM machine 10, as are represented schematically in Figure 4e. The secondary magnetic flux path is isolated from the rotor and rotor magnetic circuit.

**[00057]** Primary magnetic circuit 46 includes rotor 12, rotor air gap 24, bridge 40 and the portion of stator teeth 30 between rotor 12 and bridge 40. Primary magnetic circuit encircles primary winding 22 and, in use (as described further below) either causes or is caused by a current flow in primary winding 22, depending on whether machine 10 is operated as an alternator/generator or motor, respectively. Secondary magnetic circuit 48 includes bridge 40, back iron 32 and the portion of stator teeth 30 between back iron 32 and bridge 40. Secondary magnetic circuit encircles secondary winding 24. Secondary winding 24, as will be described further below, is provided for control purposes and preferably, therefore, not connected to an output circuit of machine 10.

**[00058]** Referring again to Figure 4a, stator 20, bridge 40 and slot 28 together define two slots or openings 28' and 28", with one opening 28' for the primary winding only, and another opening 28" for the primary and secondary windings. The primary magnetic circuit encircles opening 28' while the secondary magnetic circuit encircles opening 28". In Figure 4a, the opening 28' is radially closer to the rotor than the other opening 28". Within the slot 28, bridge 40 extends a portion of the distance from the radially innermost portion of slot 28 to the radially outermost portion of slot 28 to thereby define openings 28' and 28". The designer will select the size of the bridge, as well as the rest of the stator dimensions, based at least in part on the desired properties of the magnetic circuits in the machine to yield the desired machine performance, etc. Referring to Figure 4e, bridge 40 also preferably extends the entire distance from stator faces 27 to 29 and thus is adjacent the primary winding 22 along the length of legs 22a and 22c. Leg 23' is preferably substantially parallel to winding 24 along its leg 25' extending the length of opening 28".

**[00059]** Referring to Figures 5a-5c, a second "inside rotor" embodiment of the present invention is shown. The same reference numerals are used to denote the analogous elements described with reference to Figures 4a-4d. The skilled reader will also appreciate the relative similarities and differences in construction and operation of typical "outside" vs. "inside" rotor

configurations, and thus these will not be discussed further here. Aspects of the second embodiment not specifically described below may otherwise be assumed to be made in accordance with the description of the analogous element described above.

5

**[00060]** Referring to Figures 5a and 5b, the second embodiment of the present invention is another multi-winding, multi-phase configuration. In other words, there are multiple primary windings 22 and secondary windings 24, preferably one for each phase. For clarity, only one phase is depicted.

10 Though only the windings of one phase will be described below, preferably the description will apply to the windings of all phases.

**[00061]** Referring first to Figure 5a, each phase of primary winding 22 consists of a conductor which, in a manner similar to that described above,  
15 enters a first end 27 of a slot 28a on a first side 40' of bridge 40, travels down slot 28a, crosses bridge 40 at the second (i.e. other) end 29 of slot 28a and travels back along slot 28a and exits slot 28a from the first end 27, but on a second side 40" of bridge 40 (i.e. opposite to the first side the winding entered). Primary winding 22 then continues along the first end 27 of the  
20 stator to the next appropriate slot 28b and again enters from the first end 27 of slot 28b, but preferably from the second side 40" of bridge 40 (i.e. the same side of bridge 40 as it exited the last slot 28a). Primary winding 22 then travels down slot 28b, loops around bridge 40 at the second end 29 of slot 28b, then proceeds back up slot 28b and exits the first end 27 of slot 28b, and  
25 is now again on the first side 40' the bridge piece, and so on. Primary winding 22 is thus positioned in the desired slots 28 in stator 20.

**[00062]** In this embodiment, each phase of secondary winding 24 consists of a conductor which enters one end 27 of the slot 28a occupied by the  
30 primary winding 22 of that phase and then exits slot 28s from the opposite end 29 and continues to the next appropriate slot 28b (preferably the next slot occupied by this phase of primary winding 22, as depicted in Figure 5a), and so on.



[00063] Referring to Figure 5b, the relative arrangements of primary winding 22, secondary winding 24 and bridge 40 can be seen within stator 20. Referring to Figure 5c, a schematic representation of the primary and secondary magnetic circuits flux paths 46 and 48, respectively, is shown when  
5 PM machine 10 is in use.

[00064] A third embodiment of the present invention is disclosed in Figures 6a-6f. Referring first to Figures 6a & 6c, this embodiment is an outside-rotor, 3-phase, dual "channel" PM machine, depicted with one set (i.e. "channel") of  
10 primary windings 22 absent (for clarity), as will be described in more detail below. The same reference numerals are used in Figures 6a-6f to denote the analogous elements described with reference to the embodiments above, and thus these elements will not be redundantly described here but rather addressed only as required. Aspects of the third embodiment which are not  
15 specifically described below may be assumed therefore to be otherwise made in accordance with the description of the analogous elements above.

[00065] As mentioned briefly above, and for reasons which will become more apparent below, in this embodiment, stator 20 of PM machine 10 is  
20 conceptually divided into an "a" half and a "b" half, and thus windings 22 and 24 will be described in terms of primary windings "22a" and "22b" and secondary windings "24a" and "24b". Other features associated with windings 22 and 24 may also be described as "a" or "b" specific. Primary windings 22b are not depicted in Figures 6a-6c for clarity, but may be assumed to be  
25 otherwise identical to primary windings 22a.

[00066] Referring to Figure 6a, in this embodiment three primary windings 22a are provided, namely primary windings 22a<sup>1</sup>, 22a<sup>2</sup> and 22a<sup>3</sup>, to provide the desired 3-phase configuration. Each primary winding 22a is provided with  
30 its own primary terminal 50a (see Figure 6b) for ease of connection to an associated primary circuit (not shown). Secondary windings 24a and 24b each have squirrel cage-type arrangement (i.e. with legs 42 and end rings 44) and have secondary terminals 52a and 5b, respectively, for ease of connection to an associated secondary circuit. Referring to Figures 6d and

6e, preferably (as will be described in greater detail below) each leg 42 of secondary windings 24 includes a current-limiting device such as a fuse or breaker element 54. Stator 20 has a plurality of passages 58 defined on its inner periphery to act as an oil transfer mechanism, as will also be described  
5 in more detail below. Referring again to Figure 6a, preferably paper spacers 56 are placed between primary windings 22 and stator 20, and between secondary winding 24 and stator 20, for insulation purposes.

[00067] Bridges 40 are preferably non-integral with stator 20, and thus  
10 inserted as an assembly as depicted schematically in Figure 6c, which advantageously permits the designer to select different materials for bridge 40 and stator 20. For example, a bridge material may be chosen to alter the magnetic or performance characteristics of machine 10, as will be discussed in greater detail below. Non-integral bridges 40 may also beneficially facilitate  
15 machine assembly, as explained further below.

[00068] Referring in particular to Figures 6a-6c, as mentioned this embodiment has a "multi-channel" architecture, in that a plurality of fully independent "sets" of primary and secondary windings are provided. In this  
20 case, two such sets are provided (i.e. sets "a" and "b" described briefly above), namely primary windings 22a and 22b (primary winding 22b is not shown, for clarity) and secondary windings 24a and 22b. This multi-channel architecture permits a plurality of motor/alternators to exist within the same stator, and which may either be operated conjunctively, or independently, as  
25 desired. For example, in normal machine operation, the outputs of the winding sets may be combined to provide a single output, but in the event of a fault which requires one winding set to be shut down, the remaining winding set(s) may continue operation unaffected. This feature thus permits more than one motor/generator to exist within the same machine (as is discussed in  
30 greater detail below), thereby providing redundancy which may very valuable in applications where a complete shutdown would be catastrophic.

[00069] Stator 20 has a tooth gap 36 preferably provided in accordance with the applicant's co-pending application serial number 10/393,252, filed

March 21, 2003, the contents of which are incorporated into this disclosure by reference. Though not shown specifically in this disclosure, but as incorporated by reference from the applicant's said co-pending application, tooth gap 36 is not necessary in the stator face adjacent the rotor (i.e. near  
5 28a, as in Figure 4e), but rather slots 28 may open to the opposing face (i.e. the face opposing the stator's 'rotor face' - i.e. nearer to 28b in Figure 4e) or slots 28 may have no such openings adjacent either 28a or 28b, but rather having openings only at faces 27 and 29.

10 [00070] Primary windings 22 and secondary winding 24 are preferably each composed of single conductor provided in a single turn configuration. This single conductor, single turn configuration is preferred because it reduces the probability of a short circuit within the winding. Primary windings 22 are preferably stamped or otherwise provided from sheet metal and then  
15 pre-bent into a desired shape prior to insertion into the stator. An example series of fabrication steps are shown schematically in Figure 7a.

Advantageously, bridge 40 may be inserted into the windings before insertion into the stator, and this removable bridge portion and stator architecture permits the windings to be completely pre-assembled before being inserted  
20 into the stator, thereby improving manufacturability. Referring to Figure 7b, primary windings 22 are also preferably installed in stator 20 such that they are individually radially separated from one another to provide increased anti-short circuit protection between adjacent windings.

25 [00071] Referring to Figures 6c and 6d, in this embodiment wherein bridges 40 are non-integral with stator 20, primary windings 22 may be "pre-wrapped" around bridges 40 prior to assembly into teeth 30 of stator 20. When a whole-number of turns around bridge 40 are made by primary winding 22 (in this case, one turn is made), primary winding 22 enters and  
30 exits slot 28 of stator 20 between from the same side, as described above. This design feature advantageously permits primary windings 22 to be pre-assembled with bridges 40 (and spacers 56, as desired) prior to insertion into slots 28 of stator 20. This permits traditional winding machines (and their

associated manufacturing and tolerance difficulties) to be avoided altogether in the present design.

**[00072]** Referring to Figure 8a, in use, whether in a motor or alternator mode, the interaction of magnets and primary winding 22 causes a primary flux path 46 to be set up which runs down a first portion (i.e. the upper end) of tooth 30, across bridge 40, and back up a corresponding first portion of an adjacent tooth 30, and then to and through the rotor to complete the loop, as depicted by the solid arrows in Figure 8a. This primary flux path causes (or is the result of, depending on whether PM machine is operated as a motor or an alternator) current to pass through primary winding 22 (in a closed primary circuit). Referring to Figure 8b, this current flow through primary winding 22 causes a secondary flux path 48 to be set up through a second portion (i.e. the lower end) of teeth 30, through back iron 32, back up through the corresponding second portion of an adjacent tooth 30 and then back through bridge 40 to close the secondary loop. This secondary magnetic circuit causes a secondary current to flow through secondary winding 24 (in a closed secondary circuit)

**[00073]** The magnetic flux in secondary path 48 thus loops the portion of secondary winding 24 opposite primary flux path 46, and the interaction of primary winding 22 and secondary winding 24 thus sets up a secondary magnetic circuit in machine 10. It can clearly be seen, therefore, that the magnetic flux path(s) of the present invention are entirely different than is present in a typical prior art PM machine. As will be described in greater detail below, these characteristics of the present invention present many advantages to a PM machine designer.

**[00074]** When used as an alternator, a PM machine will generate voltage and current which may be used as required, or stored for later use. Often, a conditioning step of some description is required to convert the raw output of the alternator into a more useful form (typically by varying the voltage, current and/or frequency and perhaps also rectify the output into DC current). As discussed in the Background, in a gas turbine integral-starter generator (ISG)

application, in normal operation in an alternator mode, variations in engine speed and load results in an ISG output current and voltage which requires conditioning before the generated electricity is useable by on-board aircraft systems such as electric oil pumps, fuel pumps and other accessories.

- 5 Therefore, means may be provided outside PM machine 10 to control and condition the machine output (i.e. preferably the output of primary winding 22).

[00075] However, when operated as an alternator, the present invention also permits the output the primary winding(s) 22 to be controlled to a certain  
 10 extent through a manipulation of at least the current secondary winding(s) 24, as will now be described.

[00076] Referring again to Figures 8a and 8b, it will be appreciated that, in essence, the present invention set ups a transformer-type relationship  
 15 between primary winding 22 and secondary winding 24, as is schematically represented Figure 9 by an simple equivalent circuit. In the preferred embodiments depicted in Figures 4a to 6f, the equivalent "transformer" is a 1:1 transformer, i.e. the number of turns in primary winding 22 equals the number of turns in secondary winding 24 (here, each has only one turn). In  
 20 such a "transformer", the following relationship exists between the primary and secondary windings:

$$I_{PRIMARY} * V_{PRIMARY} = I_{SECONDARY} * V_{SECONDARY}$$

25 [00077] Thus, the magnetic flux developed within secondary magnetic circuit is proportional to the current flow in primary winding(s) 22 and inversely proportional to the magnetic coupling within secondary magnetic circuit. The magnetic flux in secondary magnetic circuit is proportional to the magnetic coupling, and inversely proportional to the current flow in secondary winding  
 30 24 (i.e. the current induced in the secondary winding causes the secondary flux to be cancelled). Therefore, the current flowing in secondary winding 24 directly influences the current generated in the primary winding 22 by the rotating magnetic system of PM machine 10, and the current flow is a function

of the current flow in the primary windings. The secondary windings 24 are inductively coupled only to the primary winding 24 (excluding leakage, etc.), and thus the secondary winding 24 and secondary magnetic circuit 48 are only influenced by the flux in the primary magnetic circuit 46 set up by the primary winding 24 (except in the case of a low Curie point bridge, of the type describe further below, when the bridge is at or exceeds the bridge material's Curie point temperature).

**[00078]** This aspect of the present invention permits the designer to use the secondary winding to manipulate the output of primary winding 22, and thus secondary winding 24 may be used as a source of control PM machine 10. Means for controlling the operation of PM machine are thus available within the machine itself, as the "control" current may be generated within PM machine 10, that is in secondary winding 24. In some instances, therefore, no external source of control current may be required. The novel architecture of the present invention therefore lends itself to many novel possibilities for control systems for the machine, a few examples of which will now described.

**[00079]** In one example control scheme, the output (i.e. from a primary winding 22) of PM machine 10 in an alternator mode may be controlled by mechanical means by directly influencing the current in the secondary winding 24. Referring again to Figures 6d and 6e, a current limiting device 54, such as a fuse element, is preferably provided in one or more legs 42 (preferably all legs) of secondary winding 24. Referring to Figures 8a and 8b, as mentioned, current in secondary winding 24 is a function of current in the primary winding 22. Thus, as current in the primary winding rises (such as in the case of an internal fault such as a short circuit) so, too, will the current in the secondary winding. Referring to Figure 12b, in use, when the current in secondary winding 24 exceeds a certain threshold, a fuse element 54 would "blow", thereby creating an open-circuit in secondary winding (i.e. no secondary current) and, by reason of the electrical inter-relationship between the primary and secondary circuits, the output current of primary circuit will be limited. With no current flow in the secondary winding, the flux in primary magnetic circuit 46 induces in a significant flux in secondary magnetic circuit 48.

Consequently inductive reactance is increased, which can be used limit maximum output current to a maximum synchronous impedance of machine 10. (Prior to opening of the fuse, when secondary current is allowed to flow in the secondary winding, the resulting secondary flux is in the opposing direction and thus tends to cancel the secondary flux. Hence, the operation of machine 10 is relatively unaffected by the presence of the secondary until the secondary circuit opens.) This permits the control of the machine's impedance and offers PM machine 10 intrinsic thermal protection against a short-circuit in primary winding 22 when operating in an alternator mode. Any suitable fuse may be used.

[00080] Prior to opening of fuse 54 (i.e. in normal machine operation), secondary winding 24 as disclosed in the embodiment of Figures 6a-6f operates in a simple short-circuited squirrel cage arrangement, and thus will have no perceptible effect on primary winding 22. In other words, when secondary winding 24 is fully short circuited, PM machine 10 maybe operated in a manner substantially in similar to prior art machines.

[00081] In a second example control scheme, current in the secondary winding 24 can be influenced by electronic means to control the current in primary winding 22. Direct electronic control of current in secondary winding 24 can be achieved by an impedance or other control system, such as the examples depicted in Figures 10, 11a and 11b which provide proportional type or other control adjustments of the current in secondary winding 24, to thereby control the current in primary winding 22.

[00082] Figure 10 shows an example of a simple arrangement for solid state secondary winding electronic control circuit 60 for control secondary winding 24 for machine 10. The main elements are  $D_1$  Bridge rectifier, and  $Q_1$  IGBT device (Insulated Gate Bipolar Transistor). The device  $Q_1$  could also be substituted by another type of device, such as a power MOSFET or other switching device. In this example, multiple secondary windings  $24^1$ ,  $24^2$ ,  $24^3$  (e.g. as in the example of a multiphase machine having a secondary winding for each phase) preferably each have similar circuits, e.g. as 60 is depicted in

Figure 10, which could be controlled by a single control system.  $V_{st}$ , the control voltage, is used to switch  $Q_1$  'on' or 'off' and, as such, may be used to control the average DC current flow in the  $D_1$  rectifier bridge and, consequently, the AC current flow in secondary winding 24. In this arrangement, secondary winding 24 preferably has multiple turns (relative to primary winding 22) such that the current being switched by the  $Q_1$  device would be stepped-down to only a fraction of the current flow in primary main winding 22 to thereby permit low current control circuitry connected to secondary winding 24 to control a high current machine output from primary winding 22. (The switched voltage at  $Q_1$  would generally still be higher than the primary machine voltage, but it will be understood that this is still practical since  $Q_1$  devices are available which operate at over 1500V). This control arrangement is useful as a voltage regulator when the output of machine 10 (i.e. the output of primary winding 22) is to be rectified for use as a DC supply or further conditioned as desired. In use, the current induced in the secondary is affected and controlled by the elements in the secondary circuit, and this control permits the current and/or voltage of the primary to be affected as desired to control the operation and behaviour of PM machine 10.

**[00083]** Many other control schemes are also possible. Referring Figure 11a, a different secondary winding electronic control circuit 60 is shown, in which the output of secondary winding 24 fed in parallel through parallel diode 62 and transistor 64 pairs (in this case the transistors are NJFETs) to permit the secondary current to be modulated to thus control the primary winding 22 output. Referring to Figure 11b, a second embodiment of a secondary winding control circuit 70 is shown, in which the output of secondary winding 24 fed to a thermally-sensitive switch 72. Still other control schemes are possible, as will be appreciated by one skilled in the art upon consideration of this disclosure.

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**[00084]** In a third example control scheme, the current in secondary winding 24 can be influenced by varying the magnetic coupling in the secondary magnetic circuit to thereby control the primary winding current. For example, referring again to the figures the configuration and material



selection for components such as stator teeth 30, back iron 32 and bridge 40 will also vary the magnetic properties of the secondary magnetic circuit, thus permitting the designer to "control" the performance of PM machine 10. In one example, described further below, the secondary magnetic circuit  
5 includes a low Curie point material such as ferrite, when the machine operates with the secondary magnetic circuit at or above the Curie temperature the effect or influence of the secondary winding would be greatly reduced.

10 **[00085]** As discussed above, non-integral bridge pieces 40 may provide benefits for the assembly of PM machine 10. Also, as briefly mentioned, the provision of a non-integral bridge permits the designer to select a different material for bridge 40. For example, additional short-circuit control can be provided to PM machine 10 in accordance with the teachings of the  
15 applicant's U.S. Patent No. 6,313,560 (the '560 patent), the contents of which are incorporated by reference into this disclosure. The '560 patent teaches that materials with a low Curie temperature (referred to as low Curie point materials in this description), such as ferrite, can be beneficially used in electric machines to provide thermal protection in the event that a fault causes  
20 normal operating temperatures to be exceeded. This concept may also be applied in the present invention, as will now be described.

**[00086]** Referring again to Figures 6a-6f, preferably bridges 40 are made of different material than teeth 30, which thereby permits the designer to alter  
25 the behaviour of the primary and secondary magnetic circuits. Most preferably, bridge 40 is made of a low Curie point material of the type described in the '560 patent, such as ferrite.

**[00087]** Referring now to Figure 12a, in use, in such a thermally-protected  
30 embodiment primary winding 22 is preferably closely thermally coupled to bridge 40 pieces to permit a fast and effective control of the machine in the fault condition. In the event of a fault that raises the temperature of a bridge 40 to or above the Curie point of the ferrite bridge material, bridge 40 begins to lose its ability to conduct magnetic flux, and thus (eventually, as

temperature increases) becomes "invisible" to the magnetic circuit in stator 30. The primary and secondary magnet circuits are thus joined into one circuit (reference 47), as magnetic flux (eventually) no longer crosses bridge 40, or flux is at least greatly reduced.

5

**[00088]** In fact, preferably, the low Curie point material is selected such that when the Curie point of bridge 40 is reached, bridge 40 doesn't completely stop magnetic flux from passing therethrough (and thus doesn't completely "shut down" the primary current down, but rather as the Curie point is reached and exceeded, the amount of magnet flux passing though the bridge is progressively reduced, thereby acting just to "turn down" the primary current, rather than shut it off completely. The amount the current is "turned down" by bridge 40 is controlled by the amount of magnetic "short circuit" experienced as a result of reaching the bridge material Curie temperature, and is thus affected not only by bridge 40 material, but also by (a) tooth pitch, (b) back iron thickness, (c) tooth length, and (d) back iron material, among other things. The designer may use this knowledge to control the "turn down" behaviour of PM machine 10 in the event a machine fault occurs.

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20  
**[00089]** To enhance the effectiveness of a low Curie point embodiment of the present invention, a close thermal coupling between the windings and the low Curie point material of bridge 40 is advantageous and thus preferred. This close coupling may be achieved by close contact between primary winding 22 and bridge 40, and/or may be enhanced by the use of bonding material between the windings and the low Curie point material.

25  
30  
**[00090]** Advantageously, the use of a low Curie point bridge material can provide thermal protection to PM machine 10 in fault situations where the current in secondary winding 24 is not high enough, for example, to blow a fuse 54 and yet continued operation of machine 10 could result in damage to the machine. Thus, the use of a low Curie point material in conjunction with the present invention can permit intrinsically redundant safety systems to be incorporated.

**[00091]** Another significant advantage of PM machine 10 is that, when a low Curie point material is employed as described, if the internal fault is a short in a loop (or loops) of the winding, the described low Curie point embodiment can permit only the faulty loop(s) to be shut down or turned  
5 down, leaving the operation of the rest of the winding essentially unaffected. The bridge and stator arrangement, in conjunction with the independent ferrite bridge portions, in effect forms a plurality of serially-connected by otherwise independent alternators within PM machine 10.

10 **[00092]** A low Curie point material may also be used in the secondary circuit for control purposes. For example, if a low Curie point material (such as ferrite) were used in the secondary magnetic circuit of the present invention, for example in the back iron, the design could permit the current in  
15 the primary circuit to be increased as the low Curie point material in the secondary circuit is heated above its Curie temperature. This may be a beneficial feature, depending on the performance criteria or specification for a particular application for PM machine 10. For example, this feature may be used to increase output to a cooling system such that the machine, operated as an alternator, both provides cooling power and controls temperature.

20

**[00093]** Referring to Figure 13a and 13b, the present invention may be provided including a cooling system including a coolant 80 (preferably oil) within PM machine 10. Oil is circulated through passages 58 inside a stator jacket 82 around and along the primary and secondary windings to assist in  
25 cooling them. In Figure 13b, an oil jet 84 in an insert 86 directs oil onto the end turn of the primary winding. If the insert 86 is made of aluminum or copper, the stray inductance of the end turn is also reduced, thereby reducing the overall machine impedance.

30 **[00094]** Accordingly, control schemes such as those disclosed above may be employed individually or may be combined as desired to permit several control features to exist contemporaneously within the PM machine. As prior art fixed-geometry PM machines typically are not controllable in any way other than by the speed at which they are operated, this controllability feature of the

present invention is of significant value to the PM machine designer, particularly in those applications where the rotational speed of the machine cannot itself be used to control machine output. The present invention also offers a robust and reliable design suitable for aerospace applications.

5

**[00095]** In essence, the present invention provides a type of internal current-limiting transformer (in the described embodiments, a 1:1 transformer, but other ratios are possible) built into the magnetic structure of the machine. The "primary" is connected electrically in series with the main output feeders  
10 of the alternator, and the "secondary" is configured preferably as a short circuit, which will become an open circuit, by means of a fuse, or other circuit interrupting or current limiting means, above a certain pre-selected temperature. Typically, the pre-selected threshold temperature will be the maximum safe sustained operating temperature of the machine, above which  
15 the machine is susceptible to thermal damage (e.g., say about 300° C when typical electric machine construction materials are used). When the secondary becomes open circuit, current flow in the primary is significantly reduced as a result of the inductive reactance of the "transformer" under no load conditions, which thereby results in an increase in the machine  
20 impedance. Preferably, the increase in machine impedance is a significant one (e.g. doubling the machine impedance), such that the short circuit current in the primary is effectively limited to a value equal to the maximum power rating of the machine. The advantage of using this "transformer" type arrangement is that each stator slot may be protected by its own "transformer-  
25 breaker", and thus the voltage that is being fused is only a fraction (e.g. 1/6<sup>th</sup> in a dual-channel 3 phase machine of the type described further below) of the total generated voltage. Consequently, the breaker/fuse in the secondary will be less likely to experience an arc when the circuit is opened.

30 **[00096]** The 'transformer' of the present invention may also be remote from the stator, such that a portion of the primary and some or all of the secondary are disposed external to the stator.

**[00097]** The net effect of the low Curie point embodiment described above is that two thermal protection schemes may be implemented in the machine, namely (1) a low Curie point type over-temperature protection scheme, which provides intrinsic and automatic reversible (i.e. non-permanent) overload protection to prevent permanent damage to the machine for moderate to severe temperature overloads, and (2) a high temperature protection scheme which will automatically react in the event that (i) the first-mentioned mechanism does not sufficiently control the short circuit current within the time desired, and/or (ii) in situations where the short circuit resistance(s) in the machine is (are) very low.

**[00098]** As discussed above, the present invention also includes a "multi-channel" design which can, among other things, offer inherent redundancy useful in aerospace applications. Referring to Figure 14, a PM machine 10 of the type described with reference to Figures 6a-6f above in essence provides a single rotor rotating relative to multiple (in the described case, two) independent stators. Thus, rotor 12 rotates relative to a "virtual" stator 20a (the portion with primary windings 22a) and also relative to a "virtual" stator 20b (the portion with primary windings 22b). This, PM machine is "two-in-one machine in this case. The output of these two "machines" may then be combined, which permits the option of operating the "two machines" as one. PM machine 10 is then preferably connected to fully redundant accessory systems, which may include redundant power conditioning units (PCU) 90, oil pumps 92, fuel pumps 94, hydraulic pumps 96 and other electrically-run accessories 98. In an gas turbine ISG application, this dual- or multi-channel design permits a fully redundant system (system A + system B, in Figure 14 ) to provided with a minimum of hardware, thereby minimizing weight and space and increasing reliability. As well, since generator efficiency is proportional to  $I^2$  losses, it is often preferable to run two "machines" like this, each at 1/2 of the output current, rather than one machine a full output current. Further, power from the two "machines" may be shared, if desired, between the PCUs with the appropriate connections, etc., to permit redundancy in the case of a "machine" or PCU failure.

**[00099]** The present invention is particularly well suited, among other things, to prevent overheating problems of an internally short circuited permanent magnet arrangement that is driven continuously, such as in the case of an internal fault in a machine 10 driven by a shaft 'S' in gas turbine engine 'GT', as depicted in Figure 15. The invention also permits a certain level of control to be attained over an alternator which is driven at variable speeds (i.e. driven by an operating propulsive aircraft gas turbine).

**[000100]** The above description is meant to be exemplary only, and one skilled in the art will recognize and changes may be made to the embodiments described without departing from the scope of the invention disclosed. For example, the machine may be single or multi-phase, single or multi-channel. The windings may have single or multi turns per slot, the number of turns of primary windings does not have to equal the number of turns of secondary winding, the number of turns of a winding not necessarily have to be a whole number, the number of primary windings does not have to equal the number of secondary windings, as one or more windings in a slot may perhaps be present in a slot. A variety of winding types may be used (squirrel cage, lap, etc.), and the windings may be any conductor(s) (i.e. single conductor, more than one wire, insulated, laminated, etc.) or may be superconductors. In multiphase machine, there may be zigzag, delta, or Y-connected windings in accordance with known techniques. There need not be an air gap between the primary and secondary winding, as long as the windings are electrically isolated from one another.

25

**[000101]** The rotor can be electromagnetic (i.e. permanent magnet not necessary), and may be provided in an outside or inside configuration, or any other suitable configuration. The bridge may be provided in one or more slots, and may be integral or non-integral with the rest of the stator. A secondary bridge may also be provided, in the form of the back iron, for example, if the secondary winding(s) are wound around the back iron. Other secondary bridge configurations are also possible.

30

**[000102]** Secondary winding may also be used for control purposes in motor mode. Other portions of the stator and rotor, such as back iron for example, may be provided of a low Curie point material to achieve the benefits of the present invention. Still other modifications which fall within the scope of the present invention will be apparent to those skilled in the art, in light of a review of this disclosure, and such modifications are intended to fall within the equivalents accorded to the appended claims. In this application, it is to be understood that the term 'alternator' is used generically to mean a device used for creating electricity, and is not intended therefore to be limited to a device for generating an output alternating current.

1 **I Claim:**

2

3 1. An electric machine operable as an alternator, the machine comprising:  
4 a permanent magnet rotor mounted for rotation about an axis;  
5 a stator adjacent the rotor, the stator including a plurality of radial slots  
6 defined in the stator between pairs of teeth, and a bridge mounted to the  
7 stator in at least one of the slots and extending between a pair of said teeth  
8 defining the at least one slot, the bridge dividing the at least one slot into at  
9 least two slot portions;

10 a first winding forming at least a portion of a first circuit, the first circuit  
11 adapted to deliver generated electricity from the machine, the first winding  
12 having a loop portion including at least a first leg and a second leg, the loop  
13 portion disposed in the at least one slot such that the first leg is disposed in a  
14 first one of said at least two slot portions and adjacent a first side of the  
15 bridge, and the second leg is disposed in a second of said at least two slot  
16 portions and adjacent a second side of the bridge, the first and second sides  
17 of the bridge opposing one another; and

18 a second winding forming at least a portion of a second circuit, the  
19 second circuit electrically isolated from the first circuit, the second winding  
20 disposed in the stator adjacent the second leg of the first winding.

21

22 2. The electric machine of claim 1 wherein the second winding is disposed in  
23 the at least one slot in the second one of the at least two slot portions and  
24 wherein the second winding is adjacent the second side of the bridge.

25

26 3. The electric machine of claim 1 wherein the bridge and said pair of teeth  
27 defining the at least one slot together form a portion of at least two  
28 magnetic circuits in the stator.

29

30 4. The electric machine of claim 1 wherein the first one of said at least two  
31 slot portions is radially closer to the rotor than the second one of said at  
32 least two slot portions.

33



- 1 5. The electric machine of claim 1 wherein the stator has a rotor face  
2 adjacent the rotor and wherein the plurality of radial slots are defined in the  
3 rotor face.  
4
- 5 6. The electric machine of claim 1 wherein the second one of said at least  
6 two slot portions is remote from a rotor magnetic circuit.  
7
- 8 7. The electric machine of claim 1 wherein said pair of teeth defining the at  
9 least one slot are immediately adjacent to one another in the stator.  
10
- 11 8. The electric machine of claim 1 wherein the second winding is connected  
12 to a control circuit.  
13
- 14 9. The electric machine of claim 1 wherein the second winding is includes a  
15 current-limiting member.  
16
- 17 10. The electric machine of claim 1 wherein the rotor is a brushless rotor.  
18
- 19 11. The electric machine of claim 1 wherein the bridge is at least partially  
20 comprised of a low Curie point material  
21
- 22 12. The electric machine of claim 11 wherein the bridge is made at least  
23 partially of ferrite.  
24
- 25 13. An electric machine operable as an alternator, the machine comprising:  
26 a rotatable permanent magnet rotor; and  
27 a stator assembly mounted adjacent the rotor assembly, the stator  
28 assembly including  
29 a plurality of openings including a first opening and a second  
30 opening, the first and second openings being separated by a portion of  
31 the stator assembly,  
32 a first electrical winding electrically connected to a first circuit,  
33 the first circuit adapted to provide electricity output from the machine  
34 when the machine is operated as an alternator, the first electrical

1 winding disposed at least partially in the first opening and at least  
2 partially in the second opening so as to at least partially form a loop,  
3 and

4 a second electrical winding connected to a second circuit, the  
5 second electrical winding electrically isolated from the first electrical  
6 winding, the second winding disposed in the second opening adjacent  
7 the first winding,

8 wherein said portion of the stator assembly defines a portion of at least  
9 two magnetic circuit paths in the stator assembly for guiding magnetic flux  
10 generated as a result of the rotor rotating about the stator, and wherein a first  
11 one of said at least two magnetic circuit paths at least partially encircles the  
12 first opening and first winding therein, and wherein a second one of said at  
13 least two magnetic circuits at least partially encircles the second opening and  
14 the first and second windings therein, and wherein the secondary magnetic  
15 circuit is defined entirely within the stator assembly.

16

17 14. The electric machine of claim 13 wherein the first electrical winding loop  
18 wraps substantially around the portion of the stator assembly separating  
19 the first and second openings.

20

21 15. The electric machine of claim 13 wherein the first opening is radially closer  
22 to the rotor than the second opening.

23

24 16. The electric machine of claim 13 wherein the first and second electrical  
25 windings are inductively coupled to one another and wherein the second  
26 electrical winding is inductively isolated from the rotor.

27

28 17. The electric machine of claim 13 wherein when the rotor is rotated about  
29 the stator assembly a magnetic flux circulating about the first one of said at  
30 least two magnetic circuits causes a magnetic flux to circulate about the  
31 second one of said at least two magnetic circuits.

32

33 18. A permanent magnet machine operable as an alternator, the machine  
34 comprising:

1 a rotatable rotor;  
2 at least a first winding electrically connected to a machine output  
3 adapted to deliver generated output electricity from the machine when the  
4 machine is operated as an alternator;  
5 at least a second winding including a current-limiting device, the  
6 second winding electrically isolated from the first; and  
7 a stator adjacent the rotor, the stator defining at least a first opening  
8 and a second opening, the first winding disposed in the first opening and  
9 second opening, the second winding disposed only in the second opening, the  
10 stator and rotor together defining a primary magnetic circuit path around the  
11 first opening, whereby relative movement between the rotor and the stator  
12 causes a primary magnetic flux to flow around the primary magnetic circuit  
13 path which thereby induces a voltage across the first winding and an  
14 associated current flow in the first winding, the stator also defining a  
15 secondary magnetic circuit within the stator around the second opening, the  
16 first and second windings being disposed in the first and second openings and  
17 the first and second openings being positioned in the stator such that, in use,  
18 said voltage and current induced in the first winding induces a secondary  
19 voltage and an associated current flow in the second winding,  
20 wherein the current-limiting device is adapted to prevent a current flow  
21 in the secondary winding when a pre-selected threshold current in the  
22 secondary winding is exceeded, the second winding thereby limiting a  
23 maximum current flow in the first winding to at least a desired maximum  
24 current flow limit.

25

26 19. The permanent magnet machine of claim 18 wherein said current flow in  
27 the first winding at least partially provides an output current of the  
28 machine.

29

30 20. A permanent magnet machine wherein the current-limiting device open-  
31 circuits the second winding when a pre-selected threshold current in the  
32 secondary winding is exceeded.

33

- 1 21. A permanent magnet machine operable as an alternator, the machine  
2 comprising:  
3 a rotor having a plurality of permanent magnetic poles;  
4 a first winding electrically connected to a machine output, the  
5 output adapted to deliver generated output electricity from the machine;  
6 a second winding including a current-limiting device; and  
7 a stator adjacent the rotor, the first and second windings  
8 disposed in the stator, the stator and rotor together defining a first  
9 magnetic circuit around a portion of the first winding, the stator defining  
10 a second magnetic circuit within the stator around a portion of the first  
11 and second windings,  
12 wherein the first and second windings are inductively coupled such  
13 that, in use, a voltage and current induced in the first winding by rotation of  
14 the rotor induces a secondary voltage and a current flow in the second  
15 winding, and wherein when a pre-selected threshold current is exceeded  
16 in the second winding, the current-limiting device prevents current flowing  
17 through the secondary winding, thereby limiting a maximum current flow in  
18 the first winding.  
19
- 20 22. A permanent magnet machine operable as an alternator, the machine  
21 comprising:  
22 a rotor having a plurality of permanent magnetic poles;  
23 a stator adjacent the rotor, the stator including at least a first winding  
24 disposed in at least one slot in the stator and a transformer disposed in the  
25 stator, the first winding inductively coupled to the rotor such that rotation of the  
26 rotor induces an output voltage and current in the first winding, the  
27 transformer electrically connected to the first winding and adapted to control  
28 at least one of said output voltage and current of the first winding.  
29
- 30 23. The permanent magnet machine of claim 22 wherein the transformer has  
31 at least a primary and a secondary winding, and wherein the primary  
32 winding is a portion of the first winding.  
33
- 34 24. An electric machine operable as an alternator, the machine comprising:

1 a stator;  
2 a permanent magnet rotor opposing the stator; and  
3 at least two windings disposed in the stator and electrically isolated  
4 from one another,  
5 wherein a first of the at least two windings comprises a primary winding  
6 in the stator for at least one of producing and consuming power, and wherein  
7 rotation of the rotor induces an output voltage and current in the primary  
8 winding, and wherein a second of the at least two windings comprises a  
9 secondary winding in the stator, the secondary winding being arranged and  
10 disposed in the stator adjacent a portion of the primary winding such that said  
11 induced current in the primary winding induces at least a voltage across the  
12 secondary winding, and wherein the secondary winding is inductively coupled  
13 substantially only to the primary winding and is inductively isolated from the  
14 rotor, and wherein the electric machine further includes means for controlling  
15 current flow in the secondary winding, said means adapted to thereby affect  
16 current flow in the primary winding.

17

18 25. A permanent magnet machine operable as an alternator, the machine  
19 comprising:

20 a rotor having a plurality of permanent magnetic poles;

21 a stator adjacent the rotor, the stator having an electromagnetic core  
22 portion defining a plurality of radially extending teeth, at least one bridge  
23 portion extending between two adjacent teeth, a first winding wound around  
24 the core and wound around the at least one bridge portion, and a second  
25 winding electrically isolated from the first winding and disposed in the stator  
26 adjacent the first winding, the second winding wrapped around the core  
27 portion but disposed remote from the bridge portion.

28

29 26. A permanent magnet machine according to claim 25 wherein the second  
30 winding includes a control member which, in use, is adapted to control a  
31 maximum current in the first winding.

32

33 27. A permanent magnet machine according to claim 25 wherein the bridge  
34 separates the secondary winding from a portion of the first winding.

1

2 28. A gas turbine engine comprising:

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a gas generator, the gas generator having a shaft adapted to output rotational power when the gas generator is operated, and an alternator drivingly connected to the shaft, the alternator including

7

8

a permanent magnet rotor mounted for rotation about an axis;

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a stator adjacent the rotor, the stator including a plurality of radial slots defined in the stator between pairs of teeth, and a bridge mounted to the stator in at least one of the slots and extending between a pair of said teeth defining the at least one slot, the bridge dividing the at least one slot into at least two slot portions;

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a first winding forming at least a portion of a first circuit, the first circuit adapted to deliver generated electricity from the machine, the first winding having a loop portion including at least a first leg and a second leg, the loop portion disposed in the at least one slot such that the first leg is disposed in a first one of said at least two slot portions and adjacent a first side of the bridge, and the second leg is disposed in a second of said at least two slot portions and adjacent a second side of the bridge, the first and second sides of the bridge opposing one another; and

25

26

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29

a second winding forming at least a portion of a second circuit, the second circuit electrically isolated from the first circuit, the second winding disposed in the stator adjacent the second leg of the first winding.

30

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33

29. A method of controlling an alternator, the alternator having a stator having at least one core portion extending between a plurality of radial teeth, a first winding wound around the at least one core portion and a second winding adjacent a portion of the first winding, the first and second

1 windings electrically isolated from one another, the method comprising the  
2 steps of:

3 rotating the rotor to induce primary current, the primary current thereby  
4 inducing a secondary current in the second winding; and

5 controlling the current flow in the second winding to thereby limit the  
6 maximum current in the first winding.

7

8 30. The method of claim 29 wherein the step of controlling comprises the step  
9 of altering the current flow in the second winding.

10

11 31. The method of claim 30 wherein the secondary current flow is selectively  
12 altered in response to an occurrence of an event.

13

14 32. The method of claim 31 wherein the event comprises the exceedance of a  
15 threshold current in the second winding.

16

17 33. The method of claim 31 wherein the step of altering comprises stopping  
18 the current flow in the second winding.

19

20 34. A method of controlling a permanent magnet alternator, the alternator  
21 having a rotor, stator and at least one winding in the stator adapted to  
22 conduct an output current induced in the winding by rotation of the rotor,  
23 the method comprising the steps of:

24 providing secondary winding electrically isolated from the at least one  
25 winding;

26 placing the secondary winding adjacent a portion of the at least one  
27 winding;

28 inductively coupling the secondary winding to the at least one winding  
29 and inductively isolating the secondary winding from the rotor, such that in  
30 use the at least one winding induces at least a voltage in the secondary  
31 winding; and

32 using the secondary winding to control at least one of the voltage and  
33 current of the at least one winding.

34

1 35. The method of claim 34 wherein the secondary winding is used to control  
2 the maximum short circuit current in the at least one winding.

3

4 36. The method of claim 34 wherein the at least one winding induces a voltage  
5 and a current in the secondary winding.



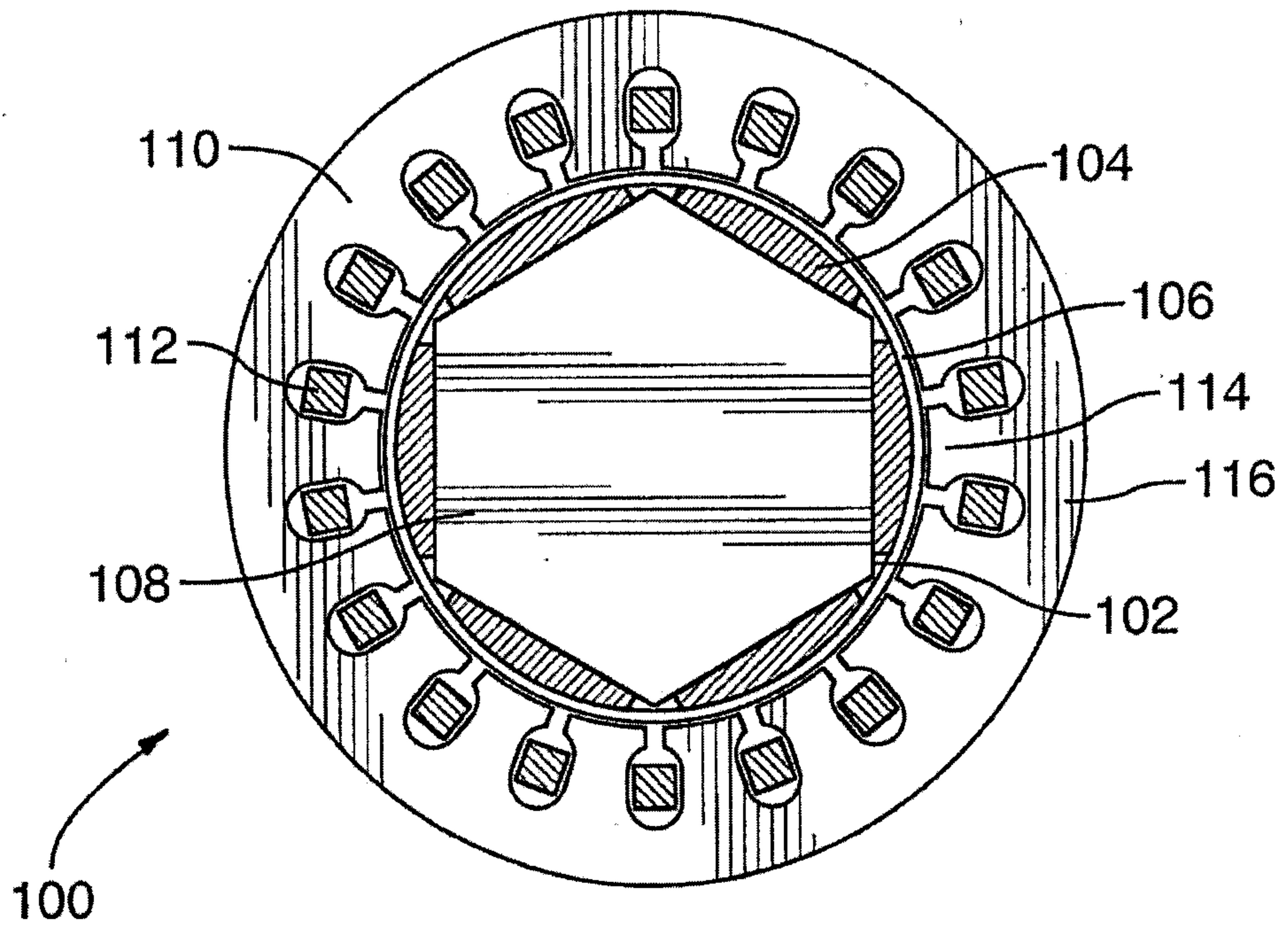


FIG. 1A  
(Prior Art)

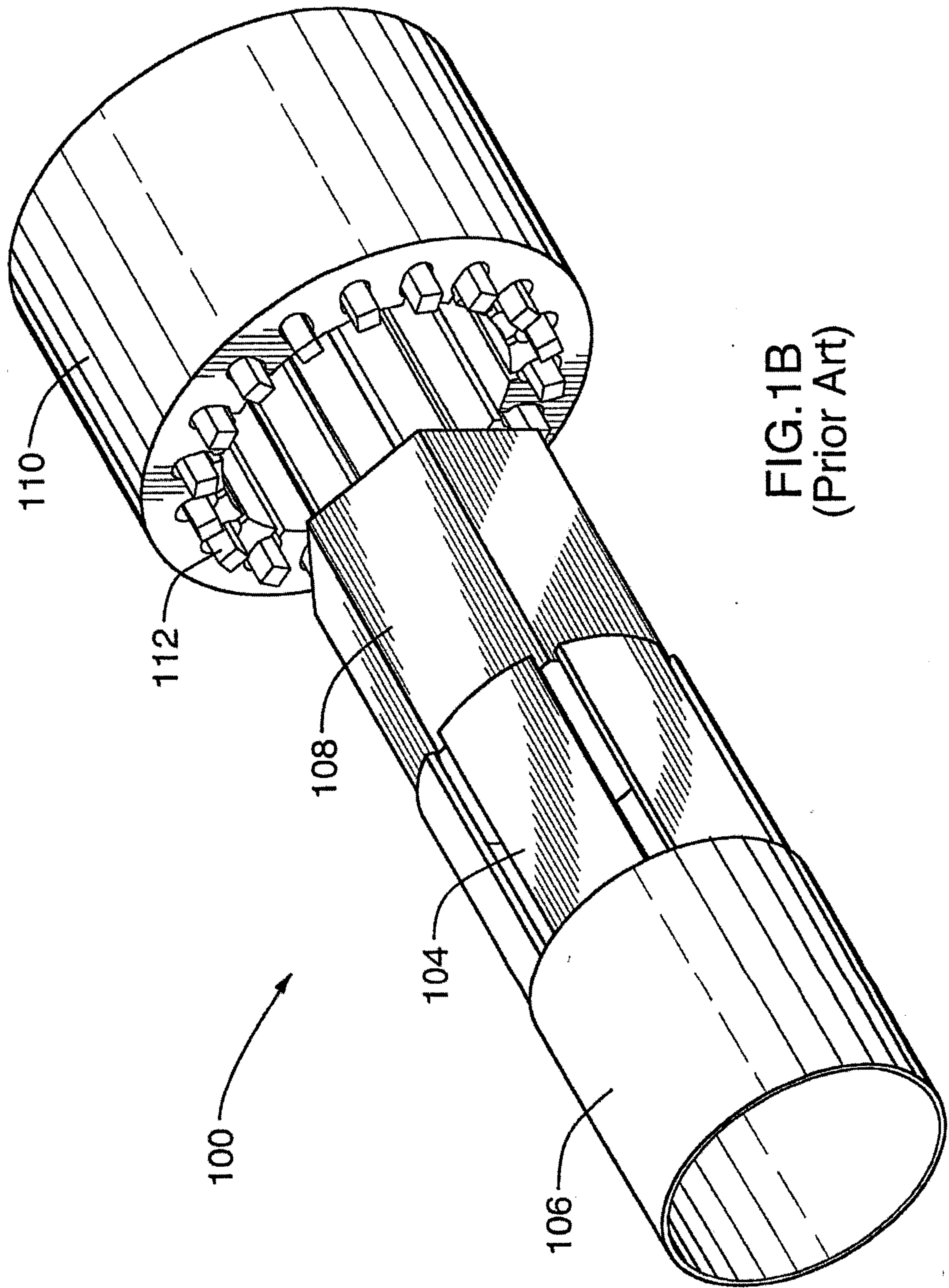


FIG.1B  
(Prior Art)

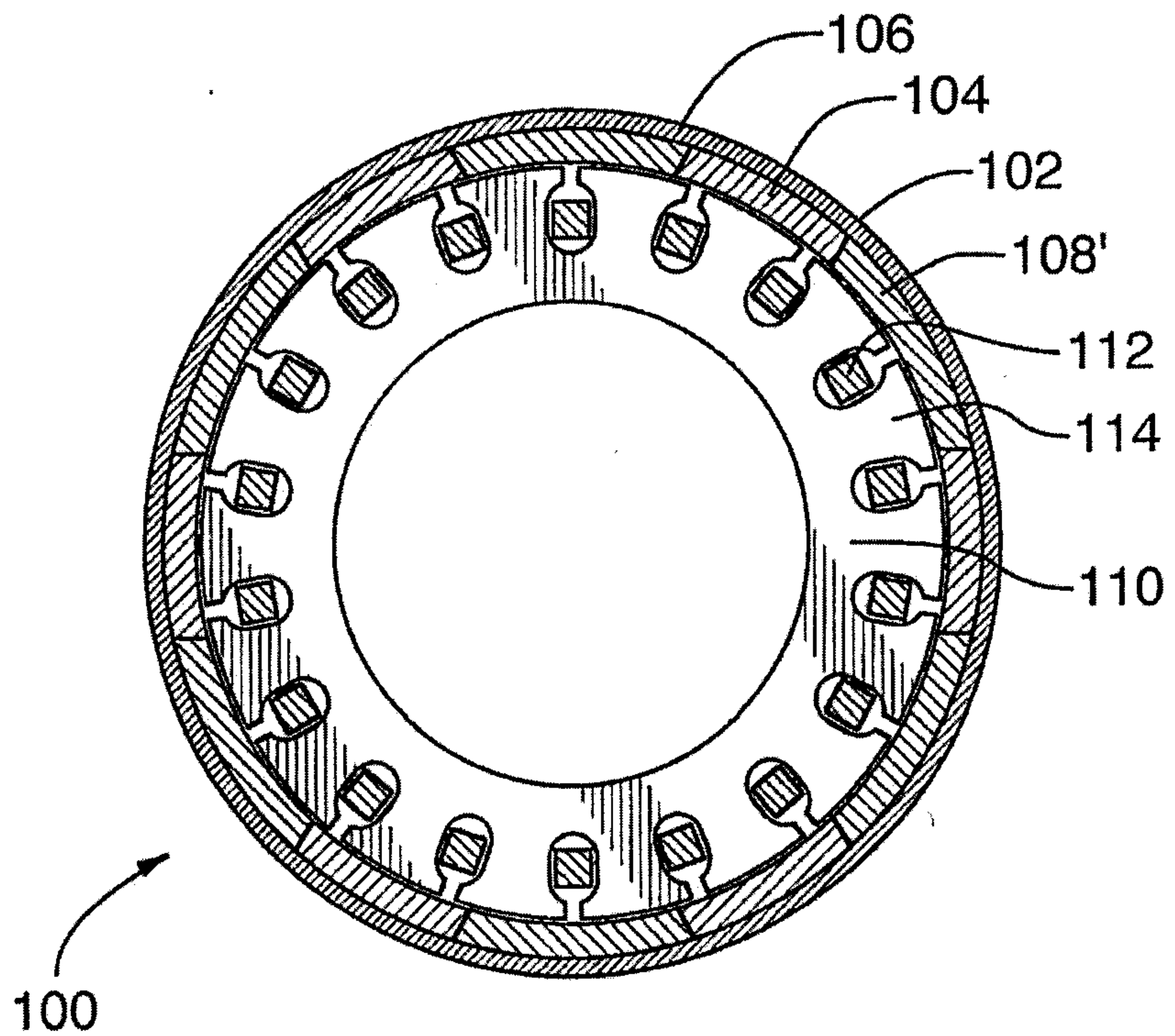


FIG.2A  
(Prior Art)

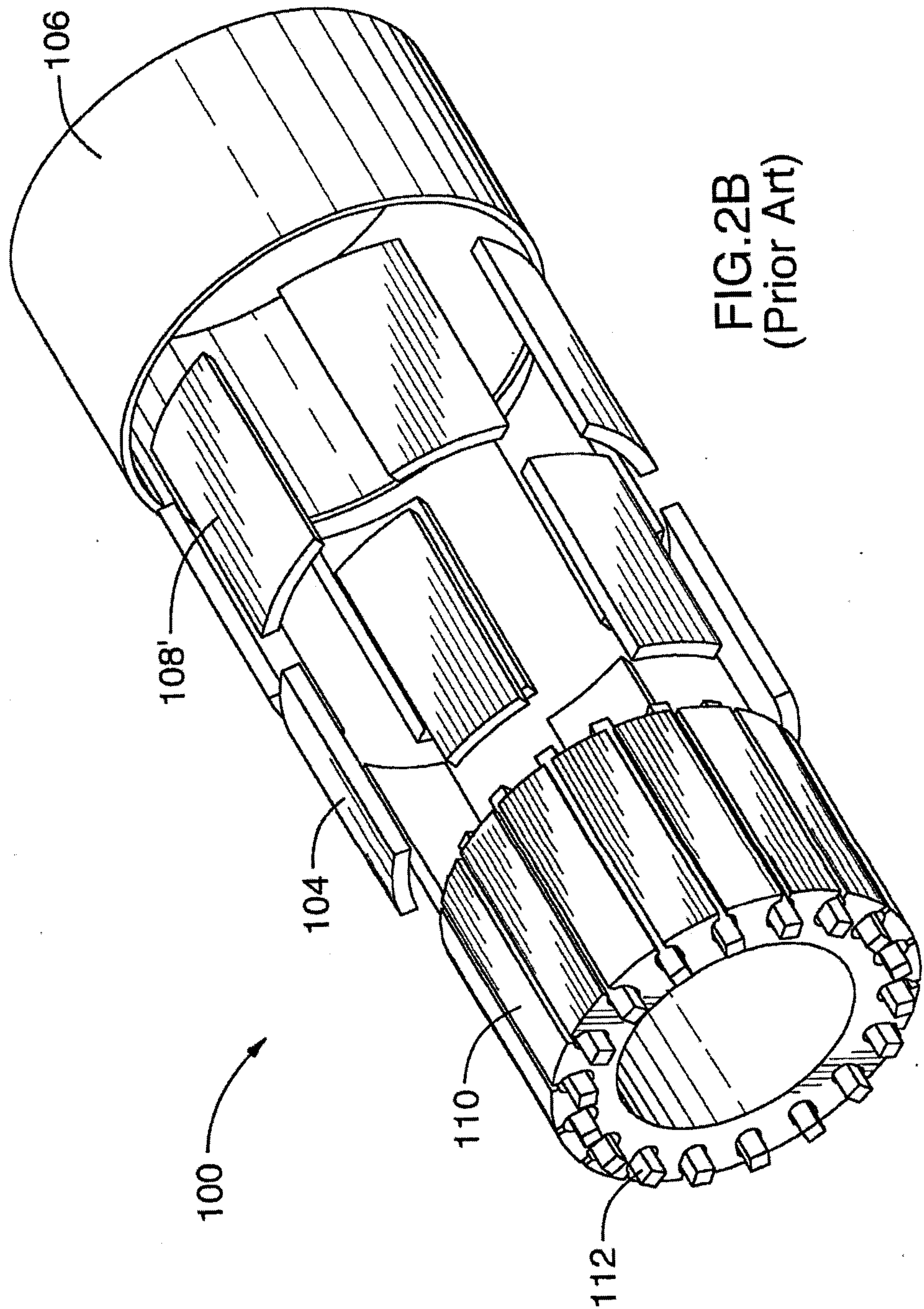


FIG. 2B  
(Prior Art)

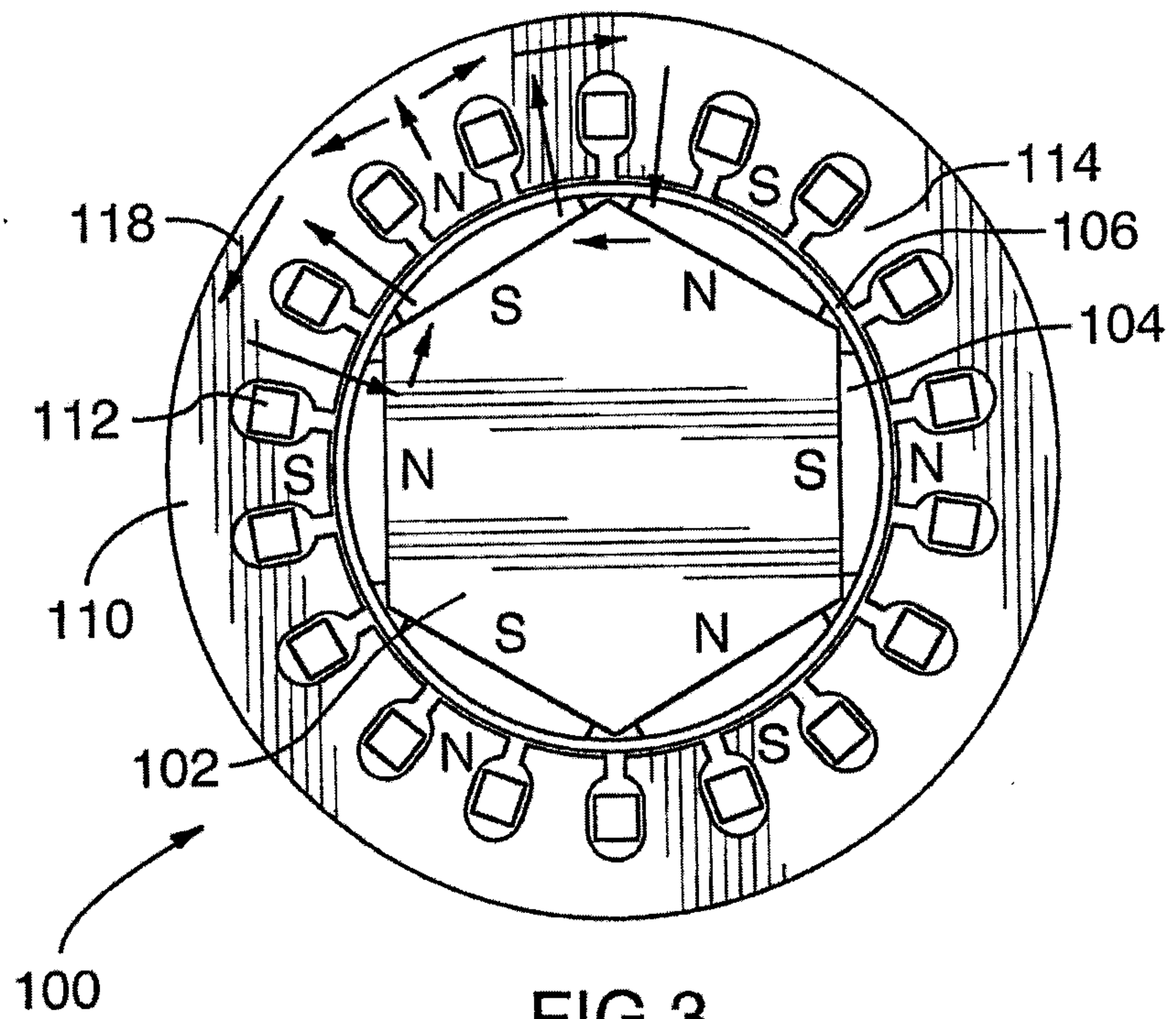


FIG.3  
(Prior Art)

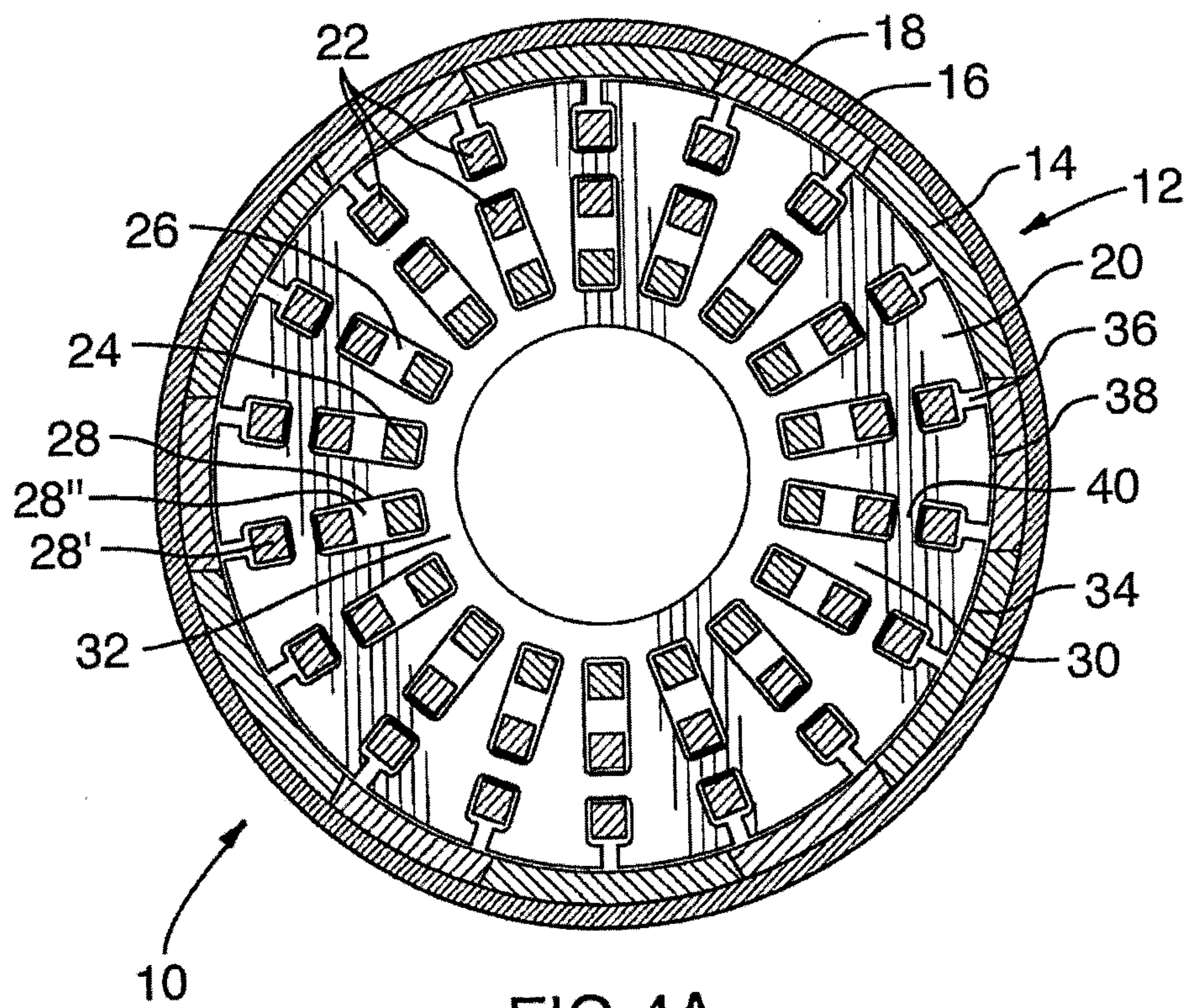
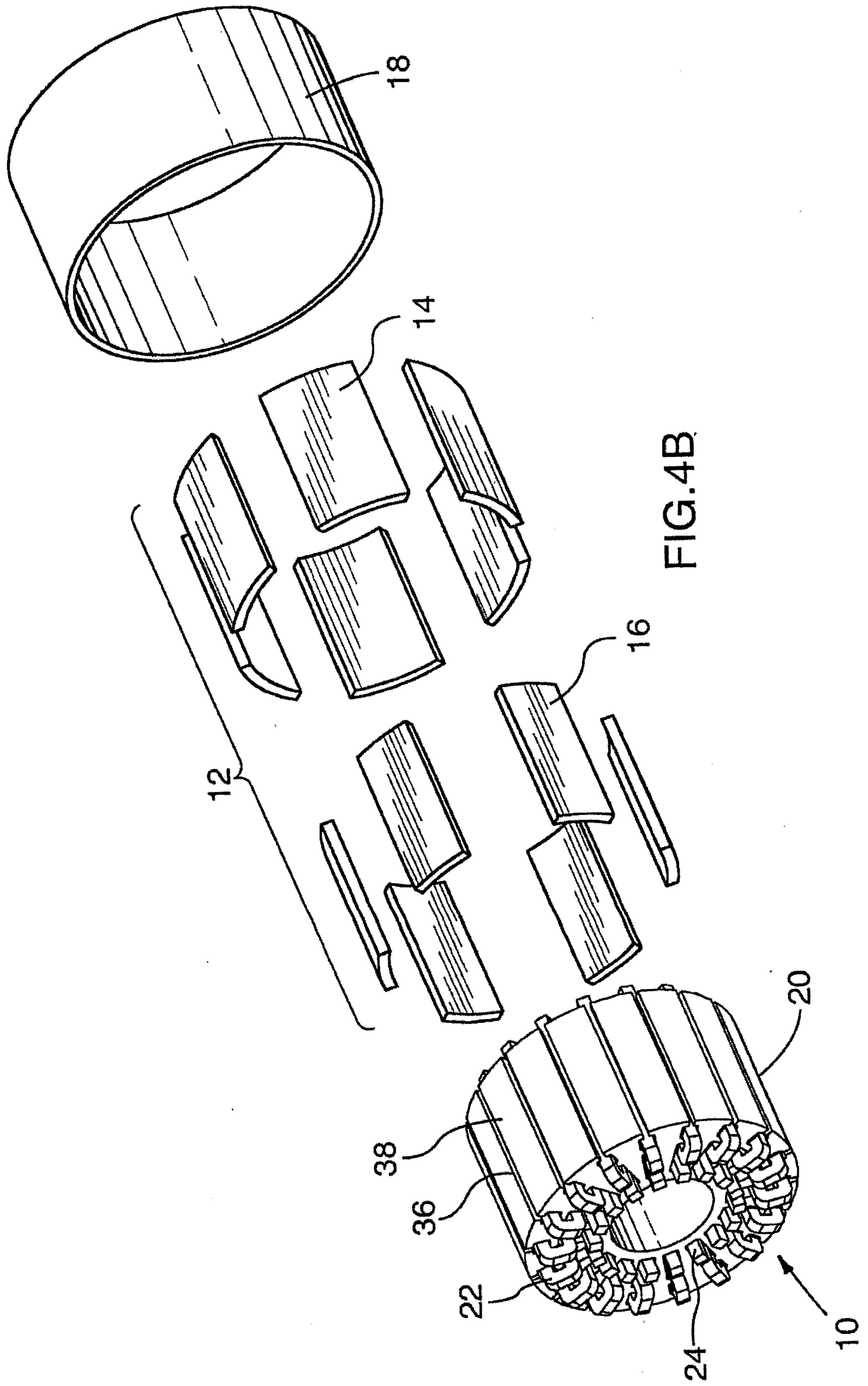


FIG. 4A

7/29



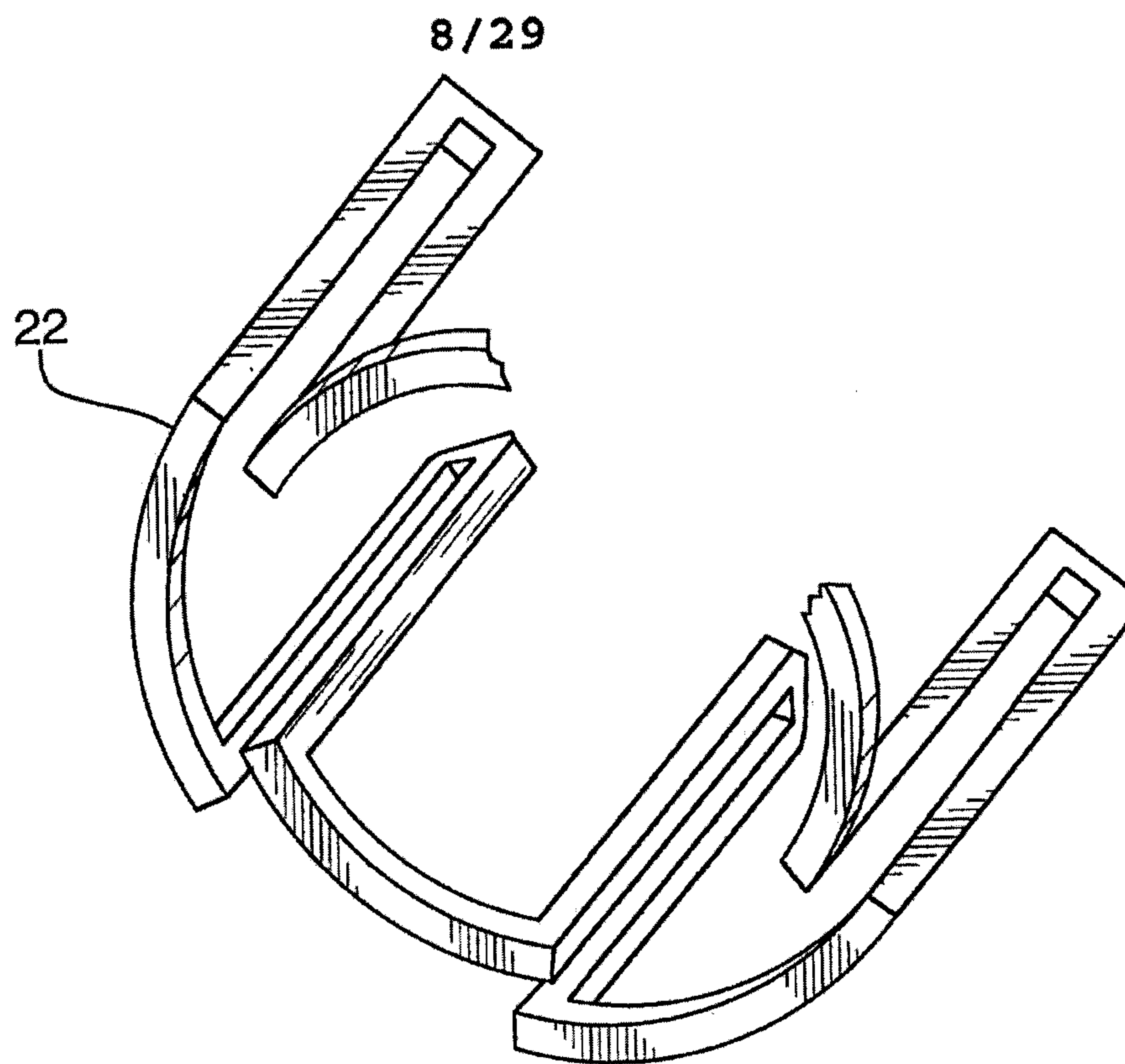


FIG.4C

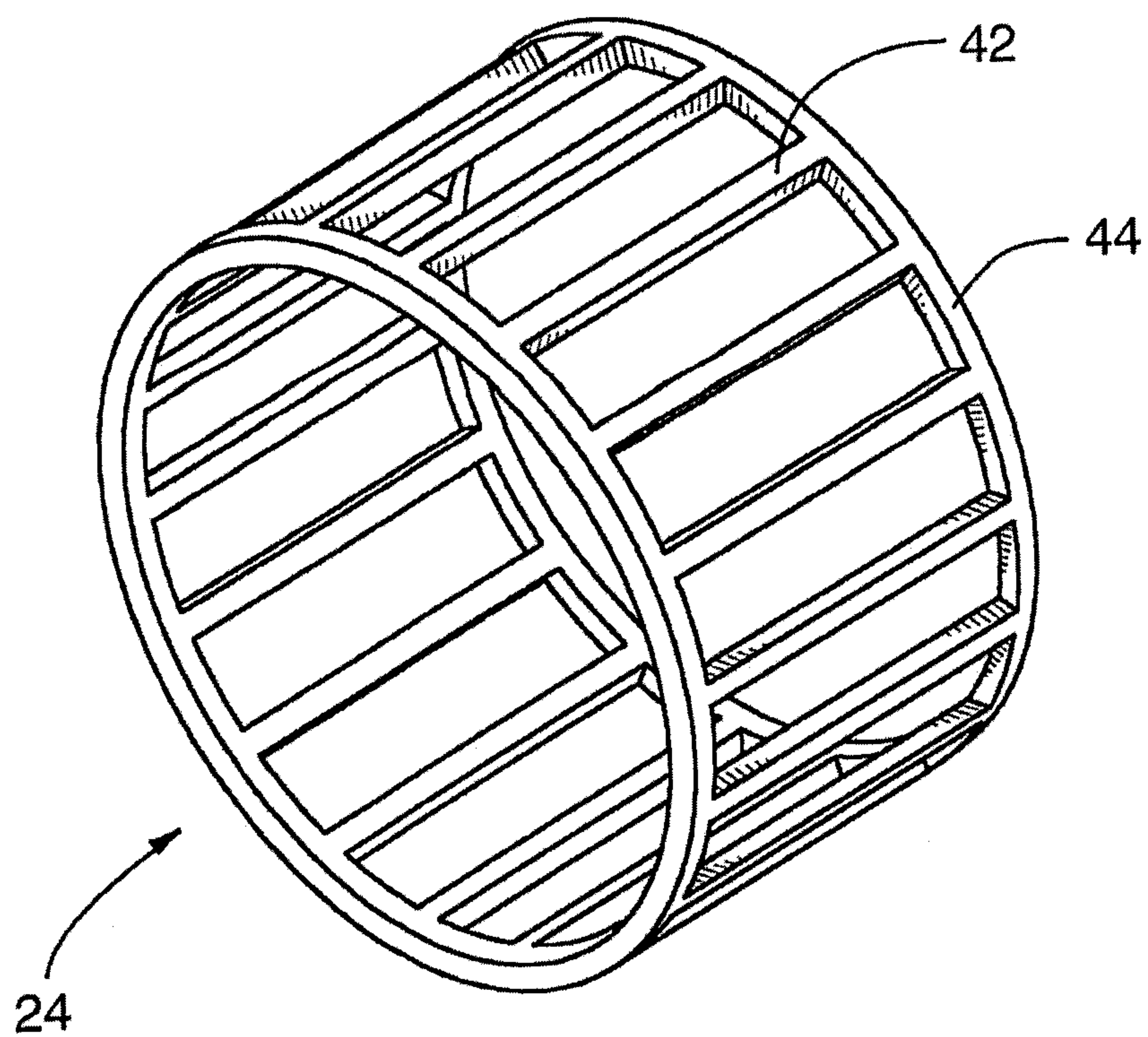


FIG.4D



9/29

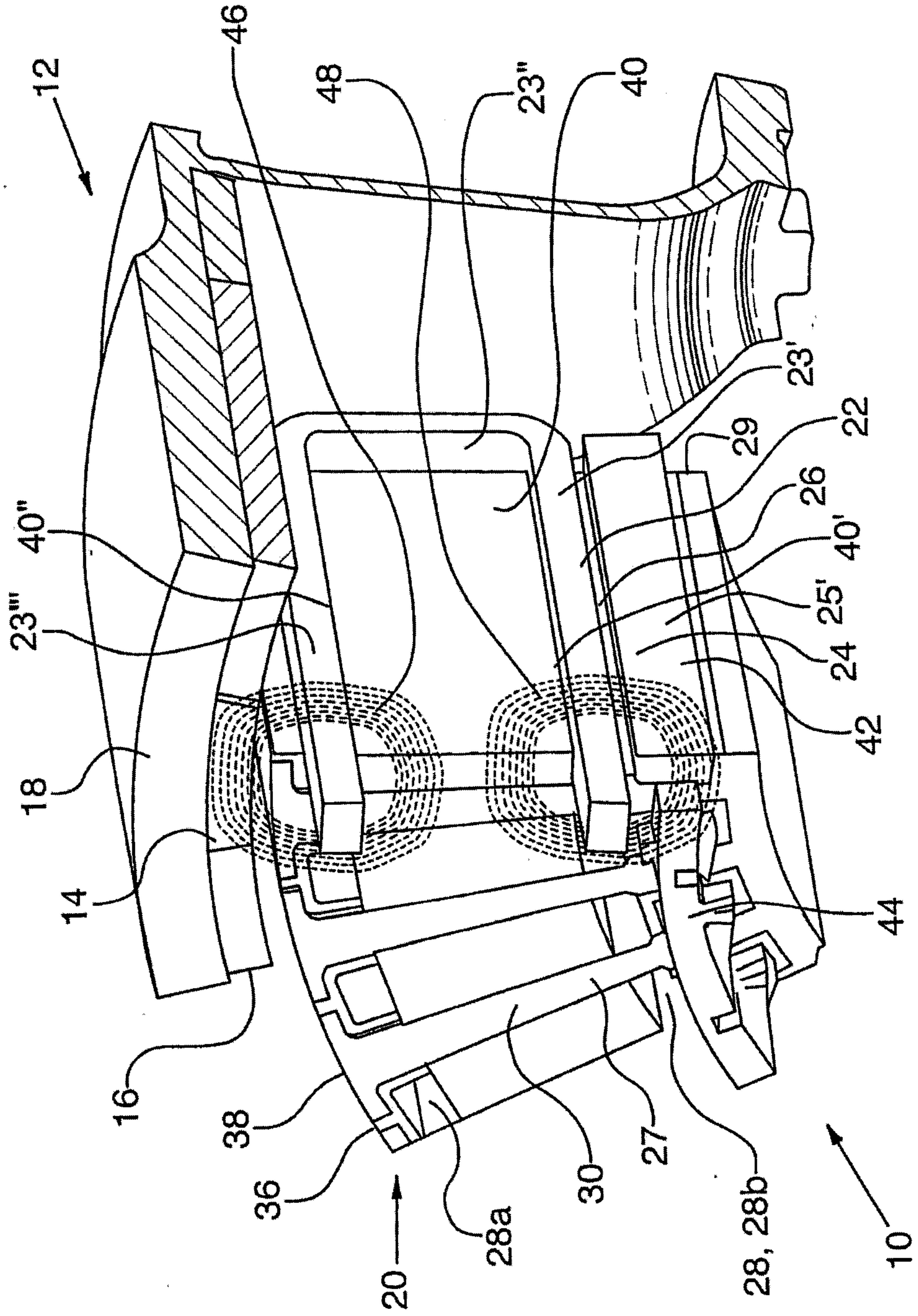


FIG. 4E

10/29

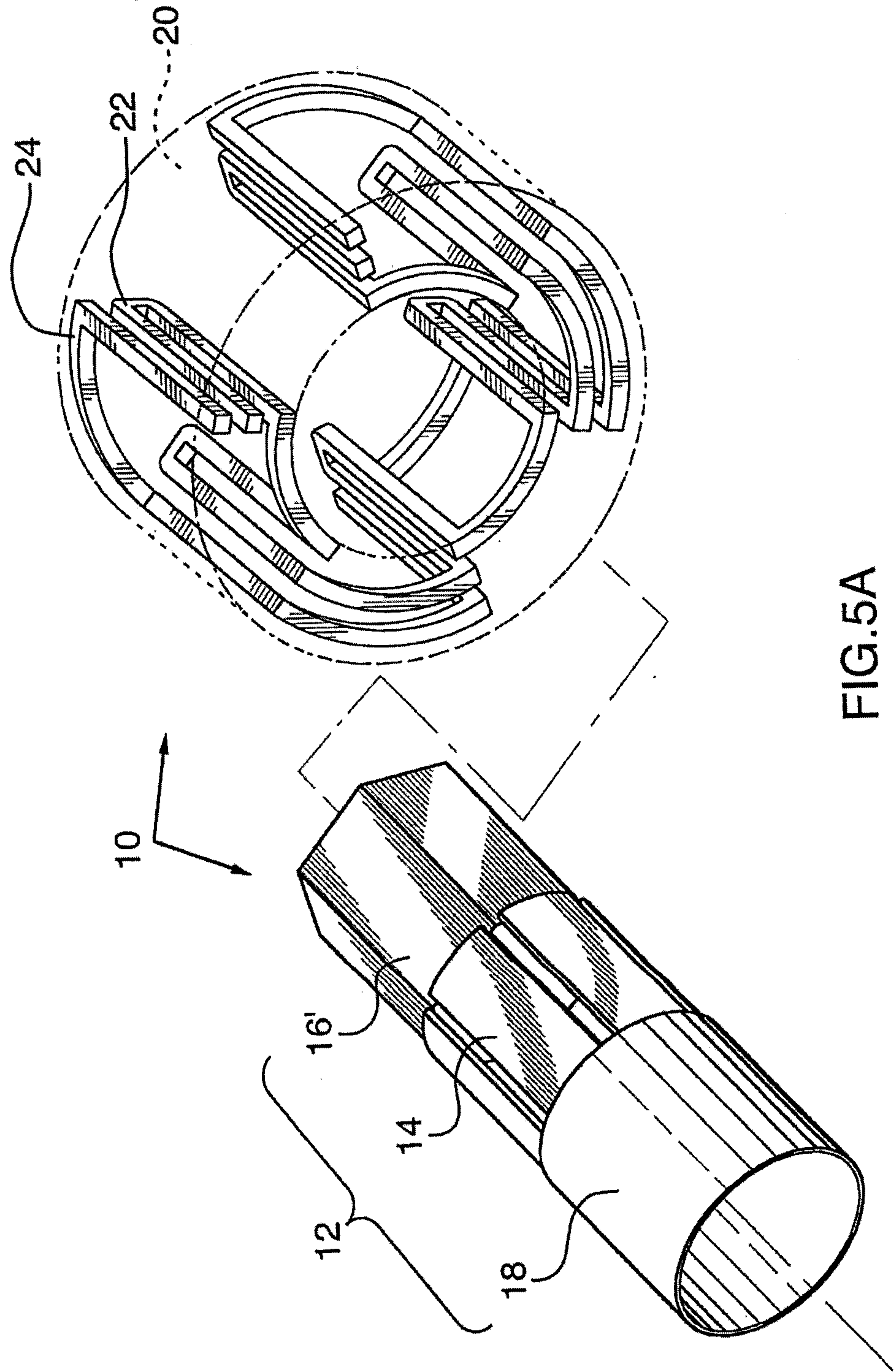


FIG. 5A

11/29

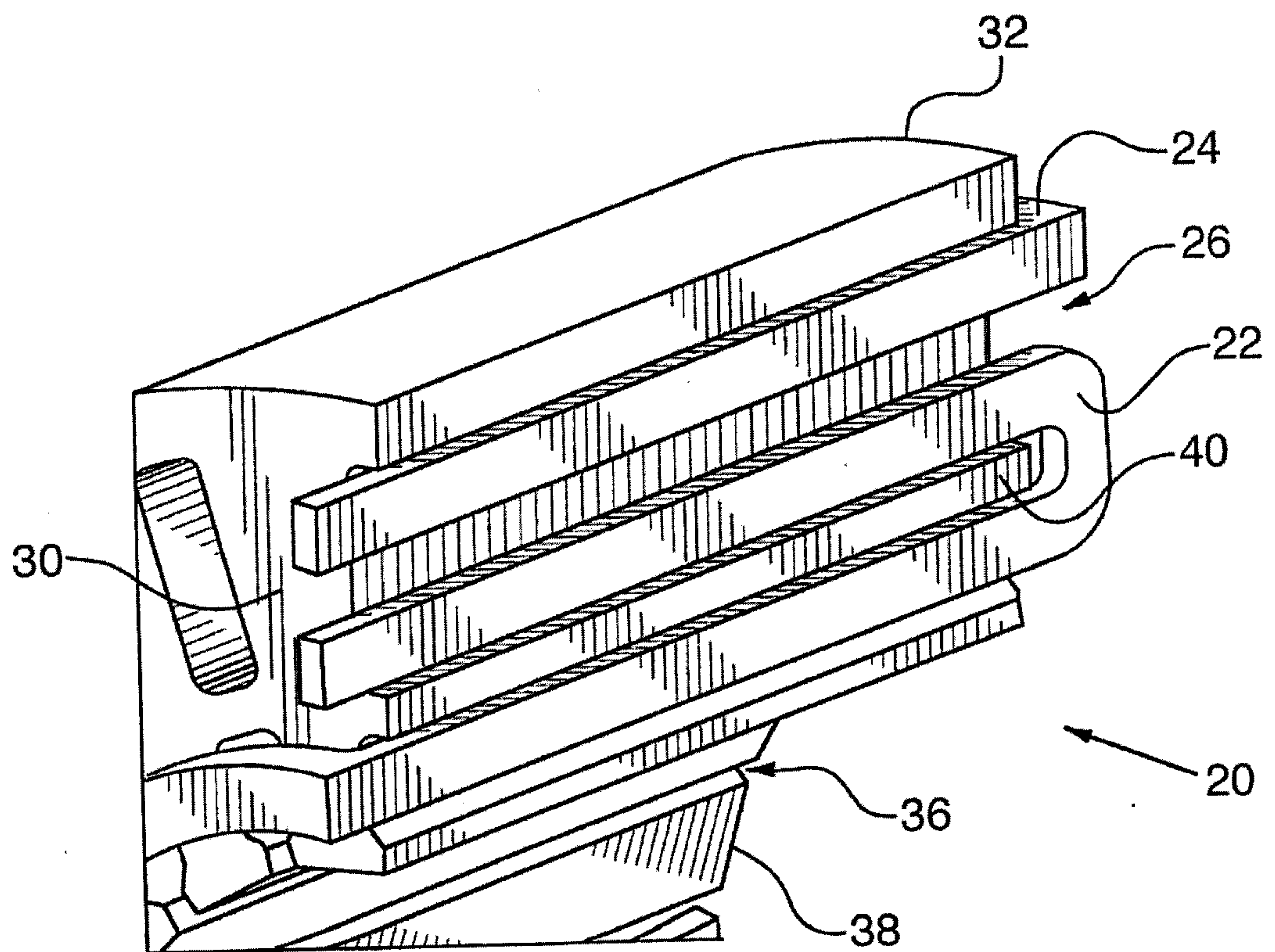


FIG. 5B

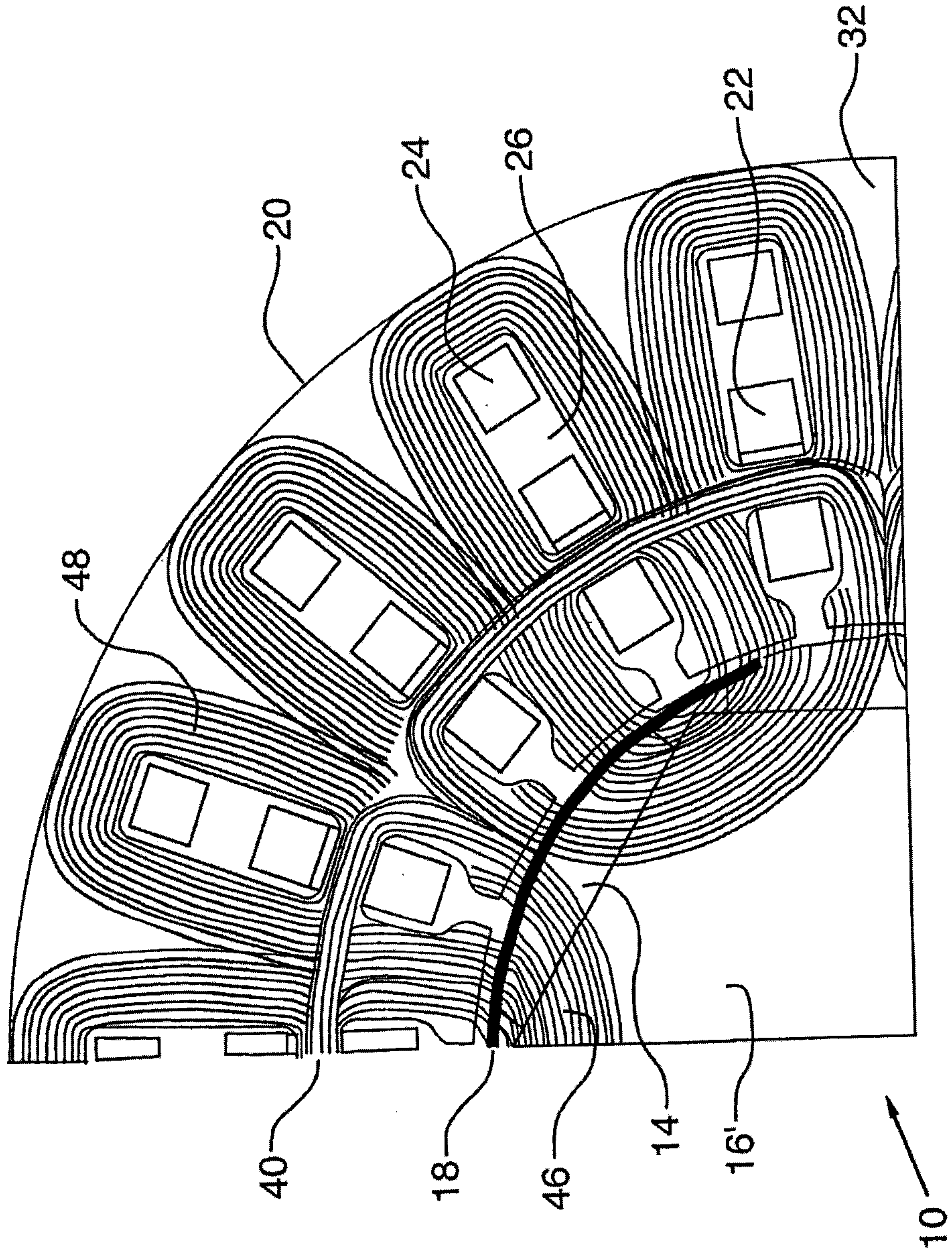


FIG. 5C

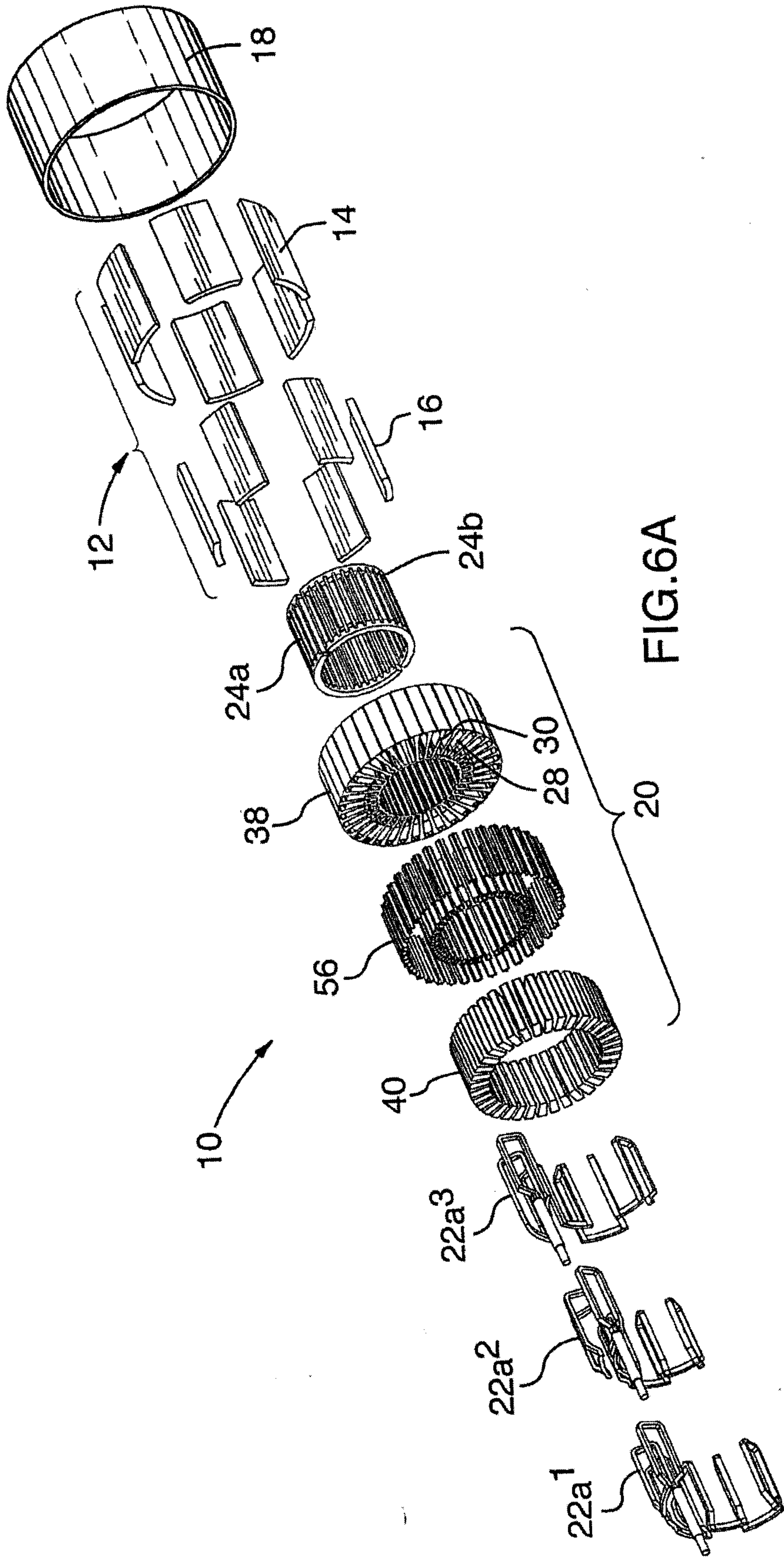


FIG.6A

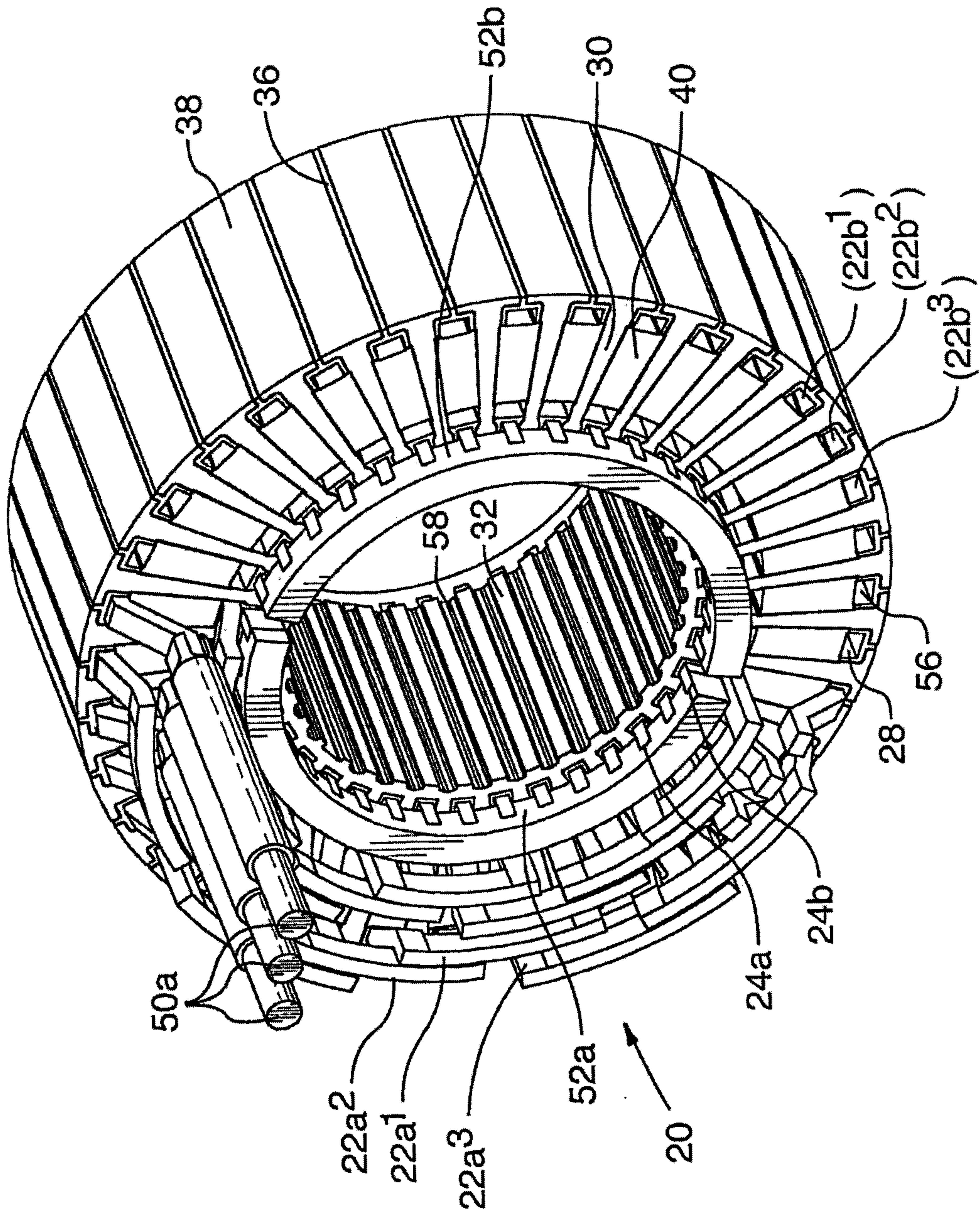


FIG. 6B

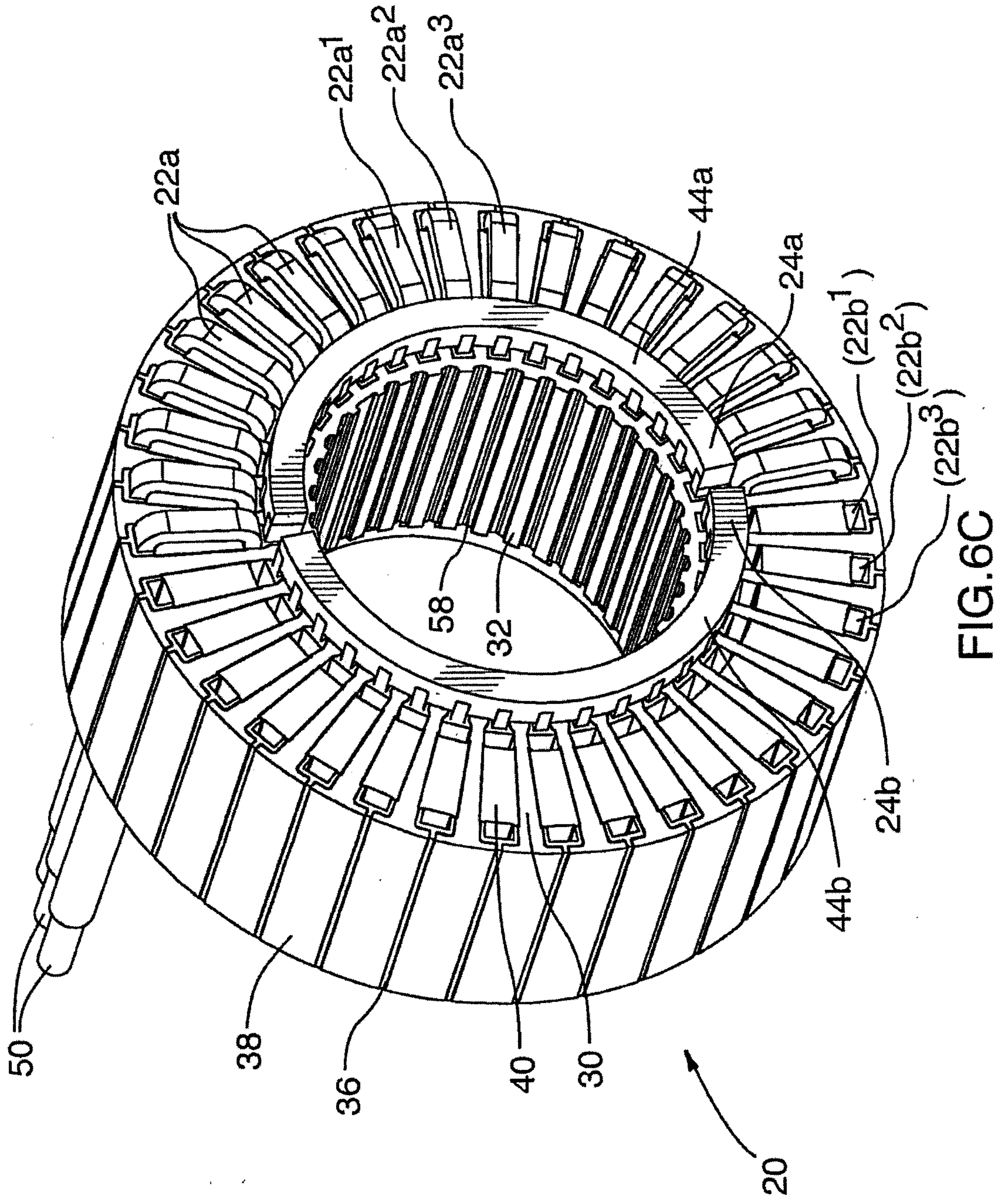


FIG. 6C

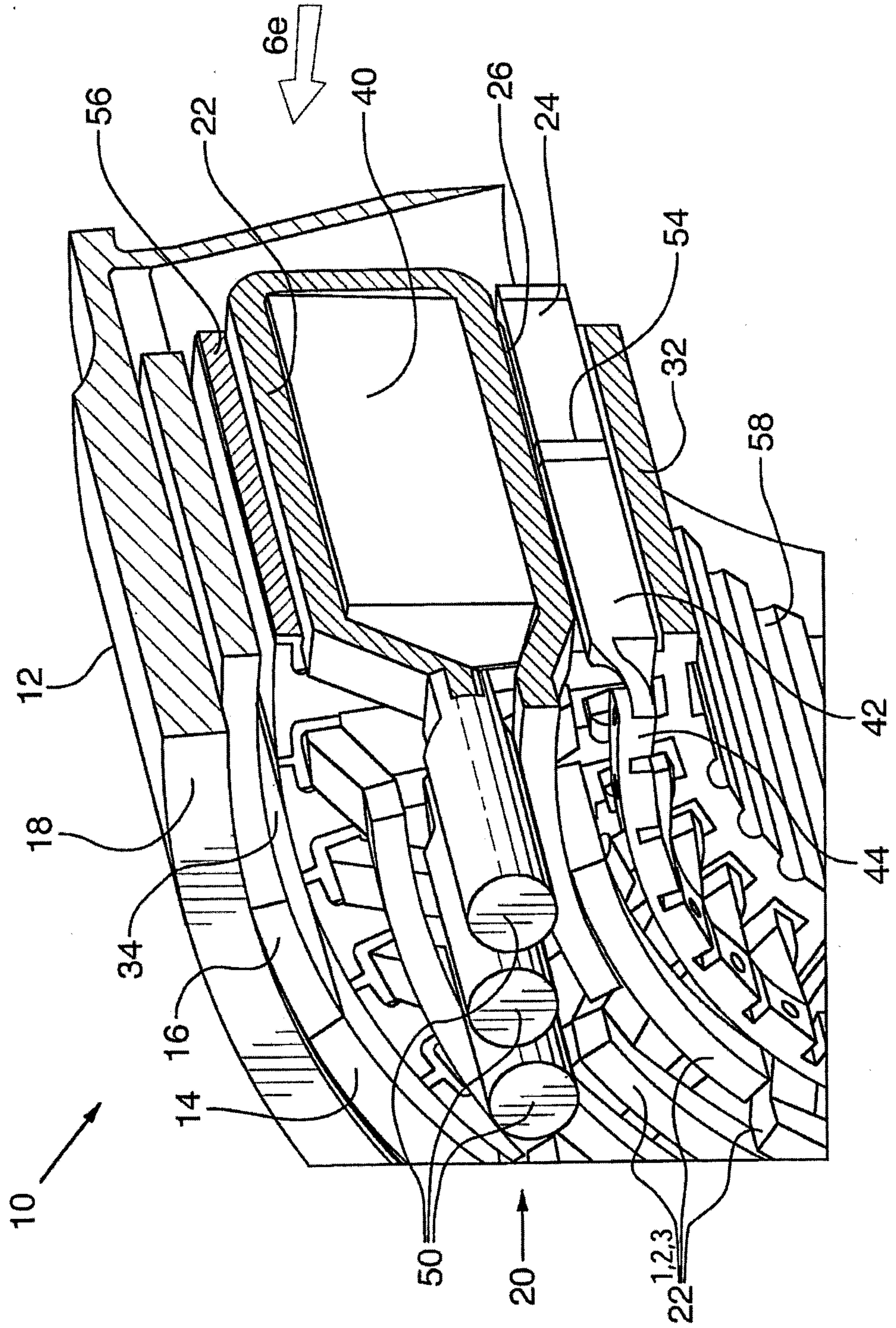


FIG. 6D



17/29

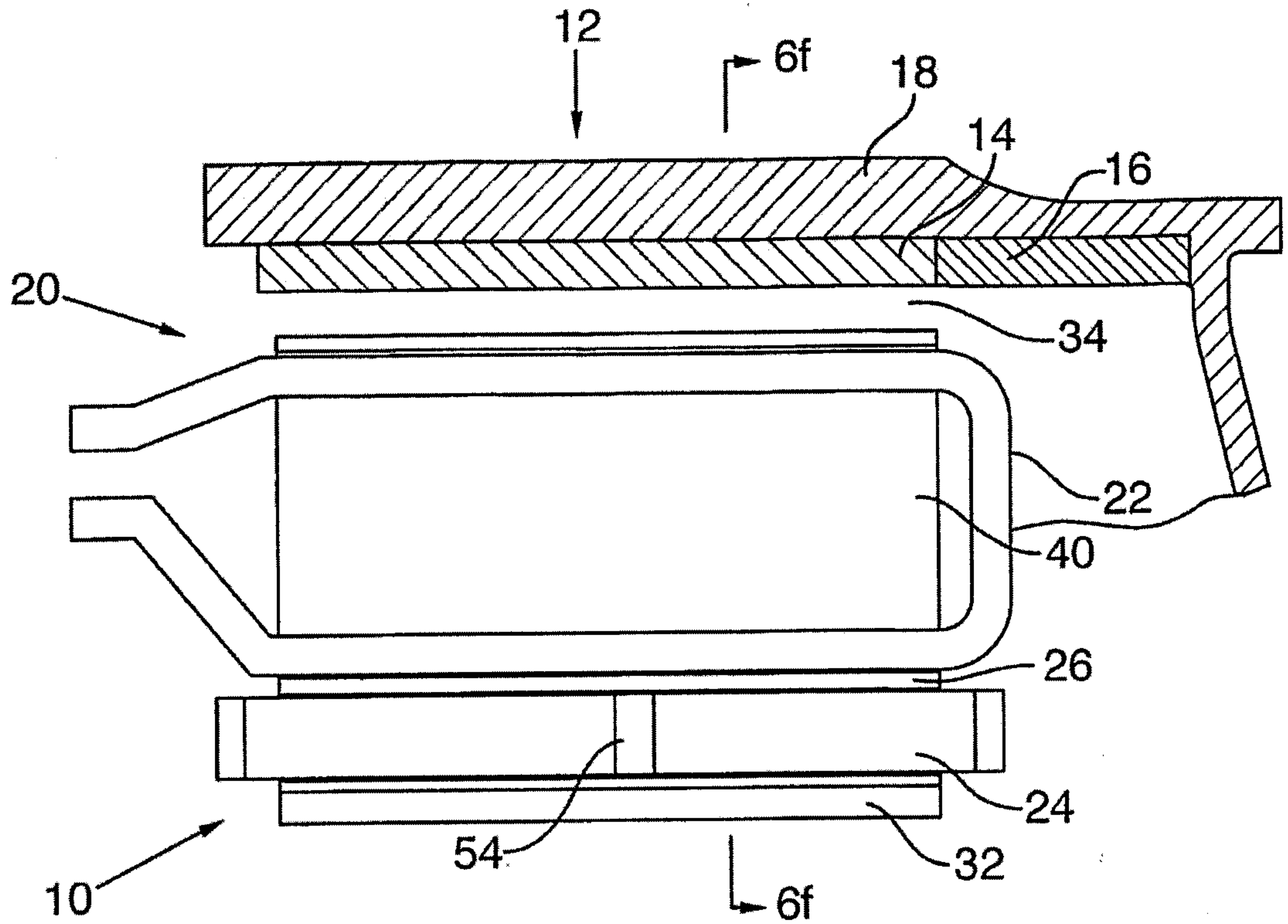


FIG. 6E

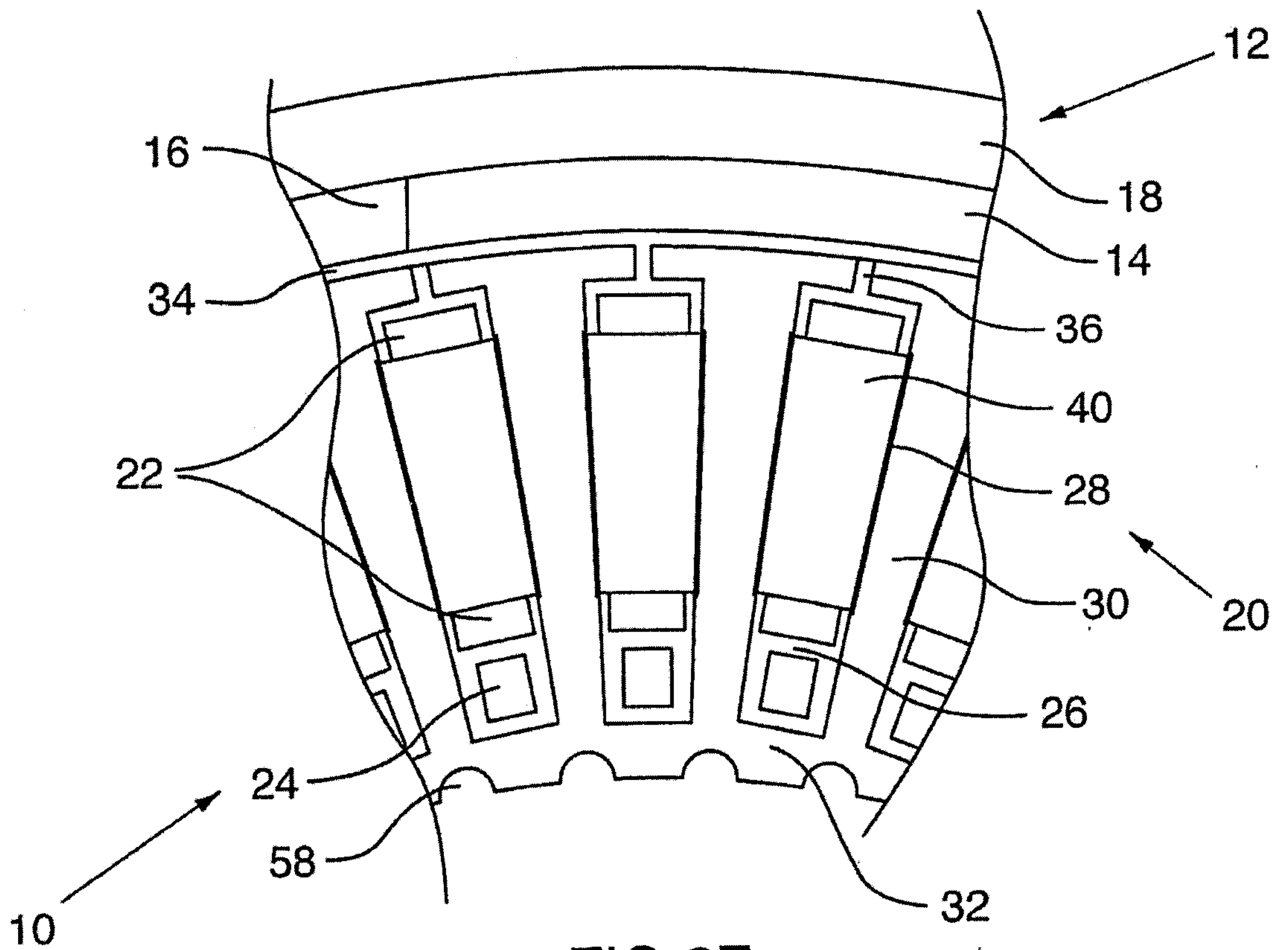


FIG. 6F

18/29

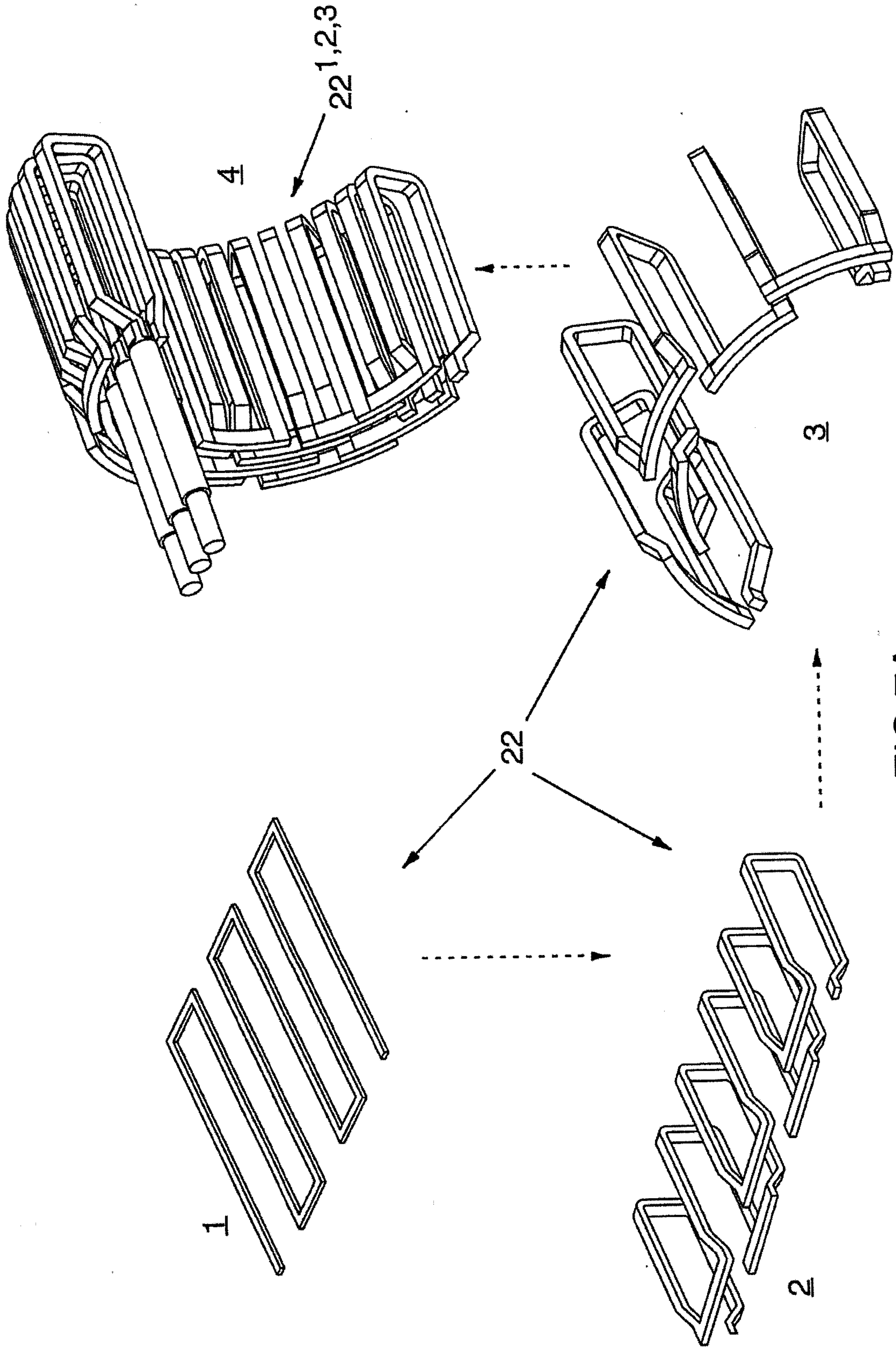


FIG.7A

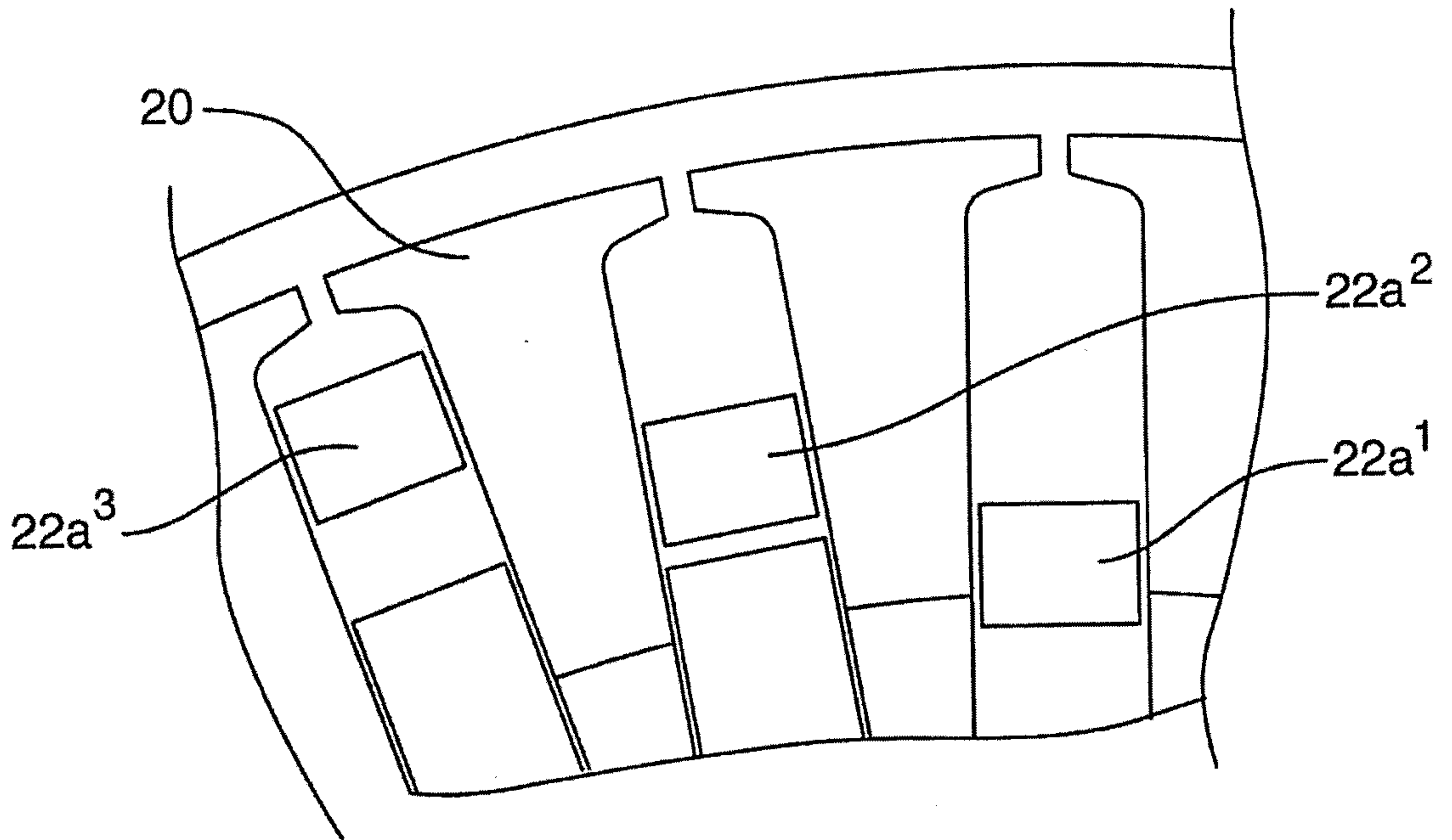


FIG.7B

20/29

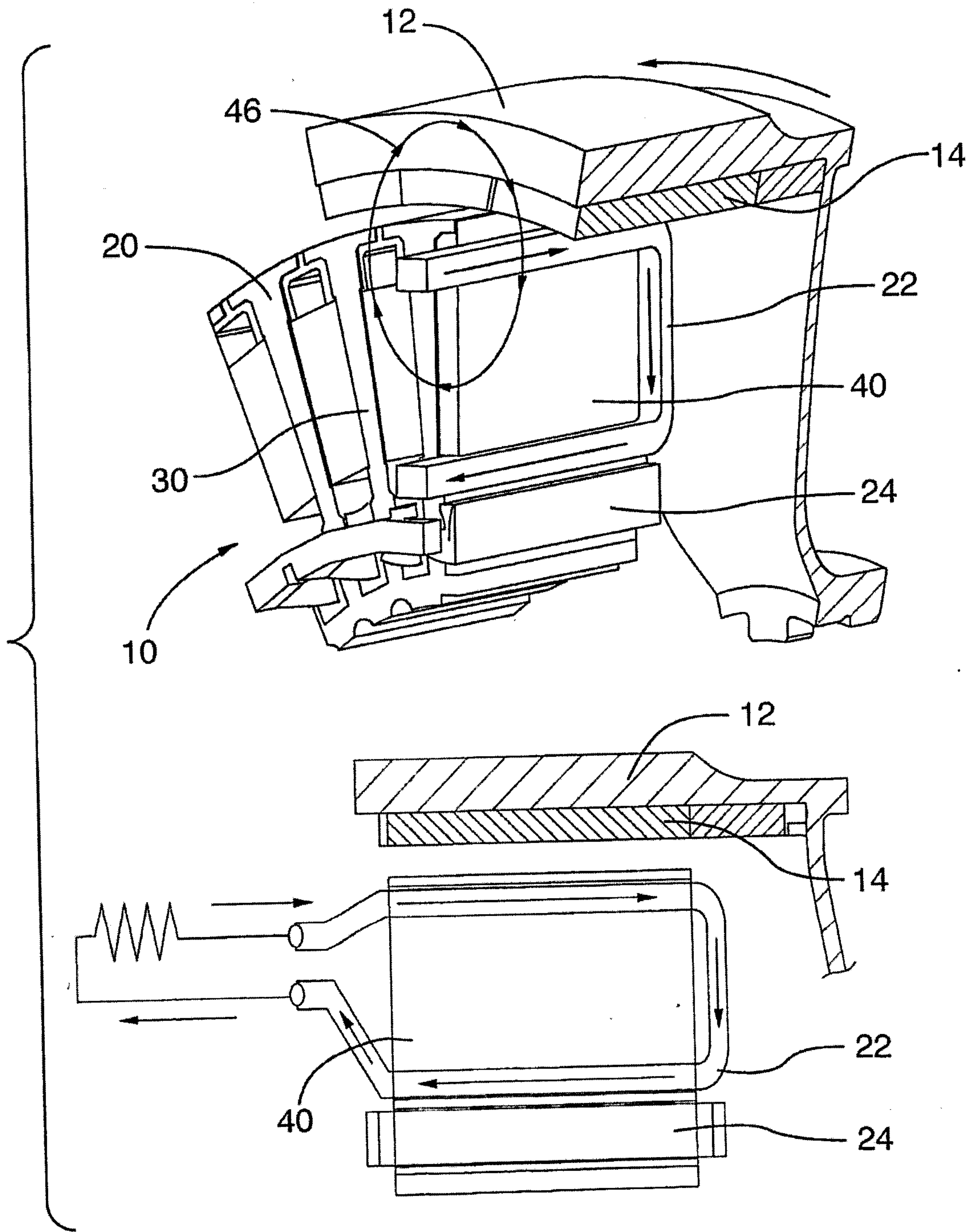


FIG.8A

21/29

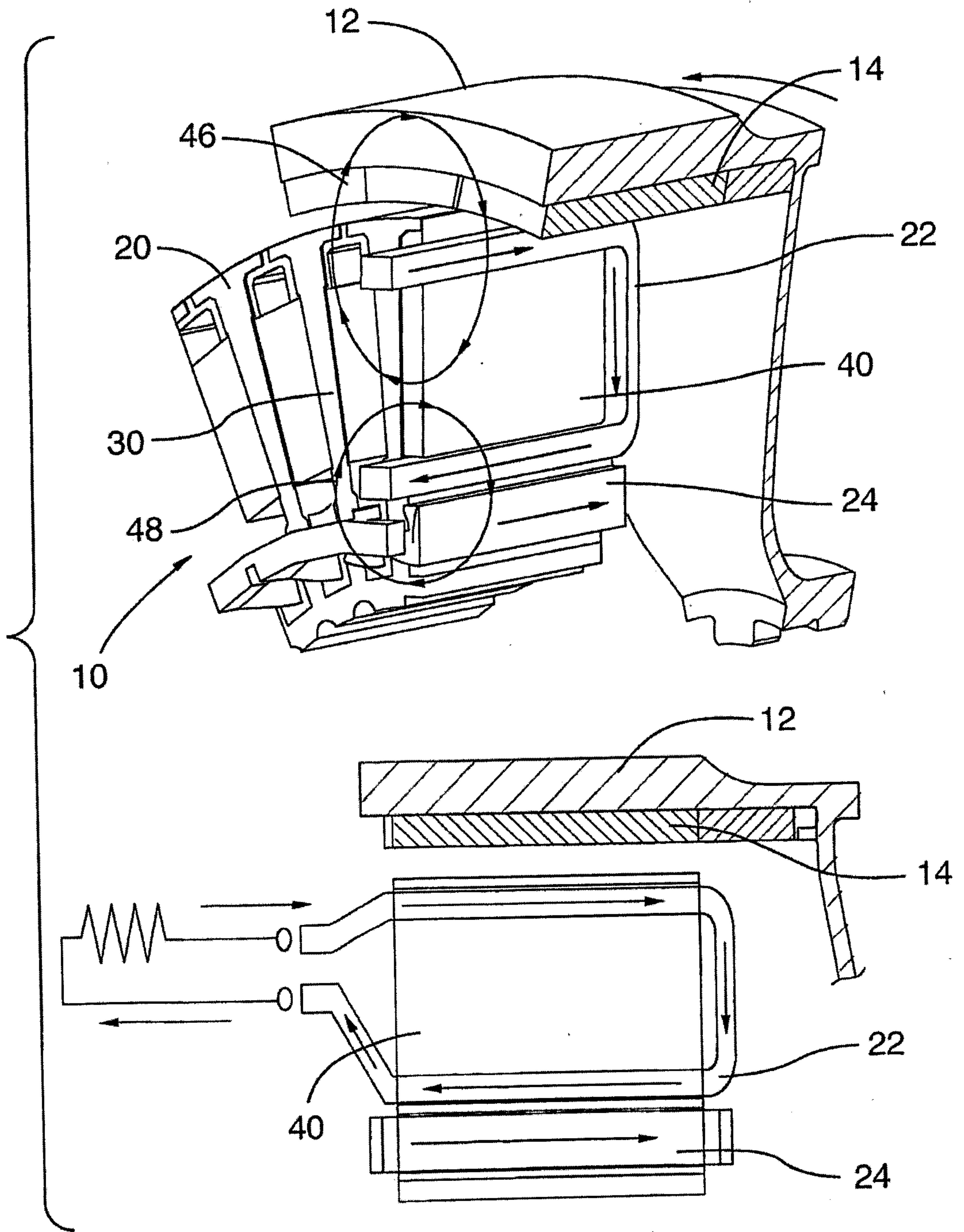


FIG.8B

22/29

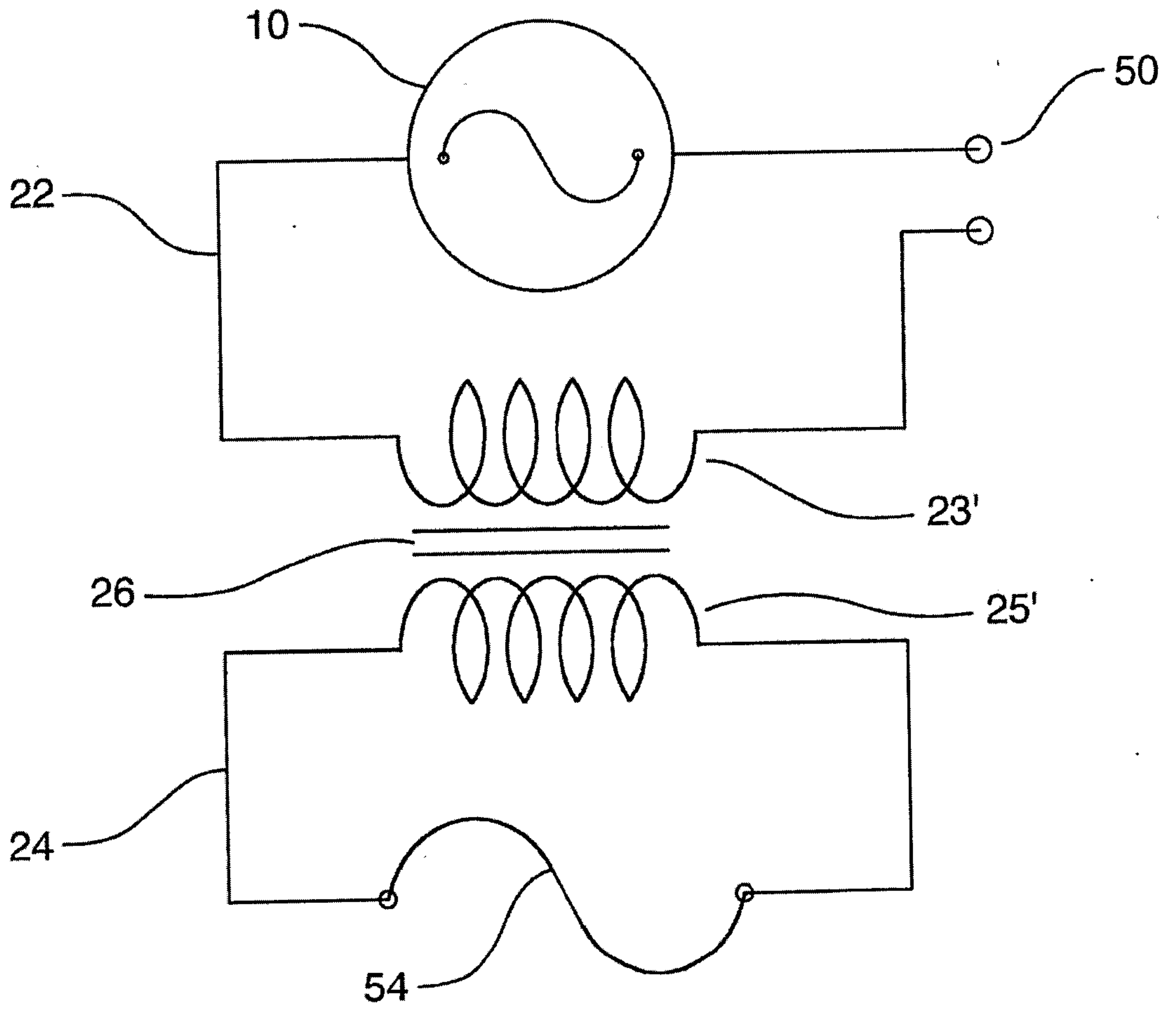


FIG.9

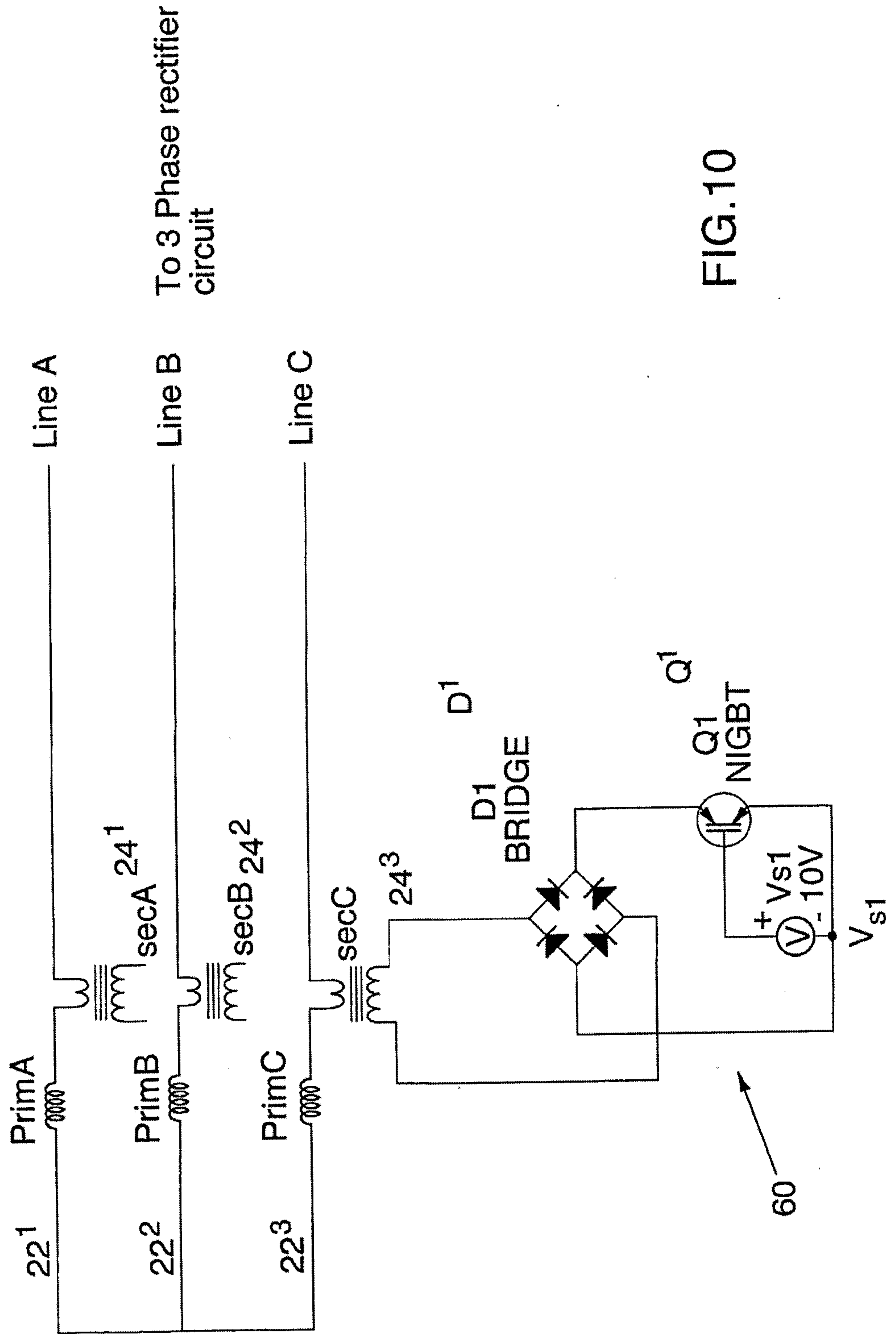


FIG.10

24/29

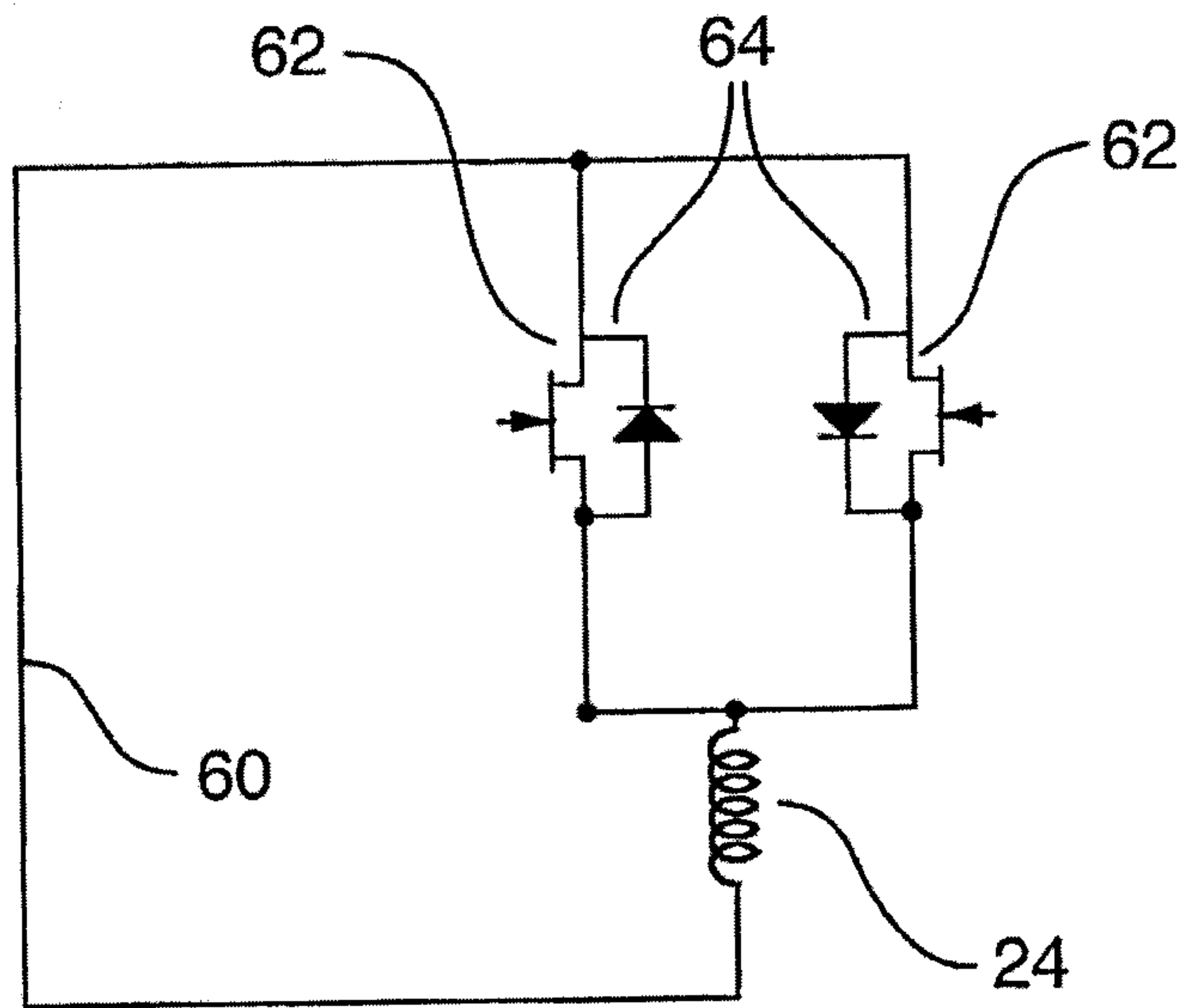


FIG.11A

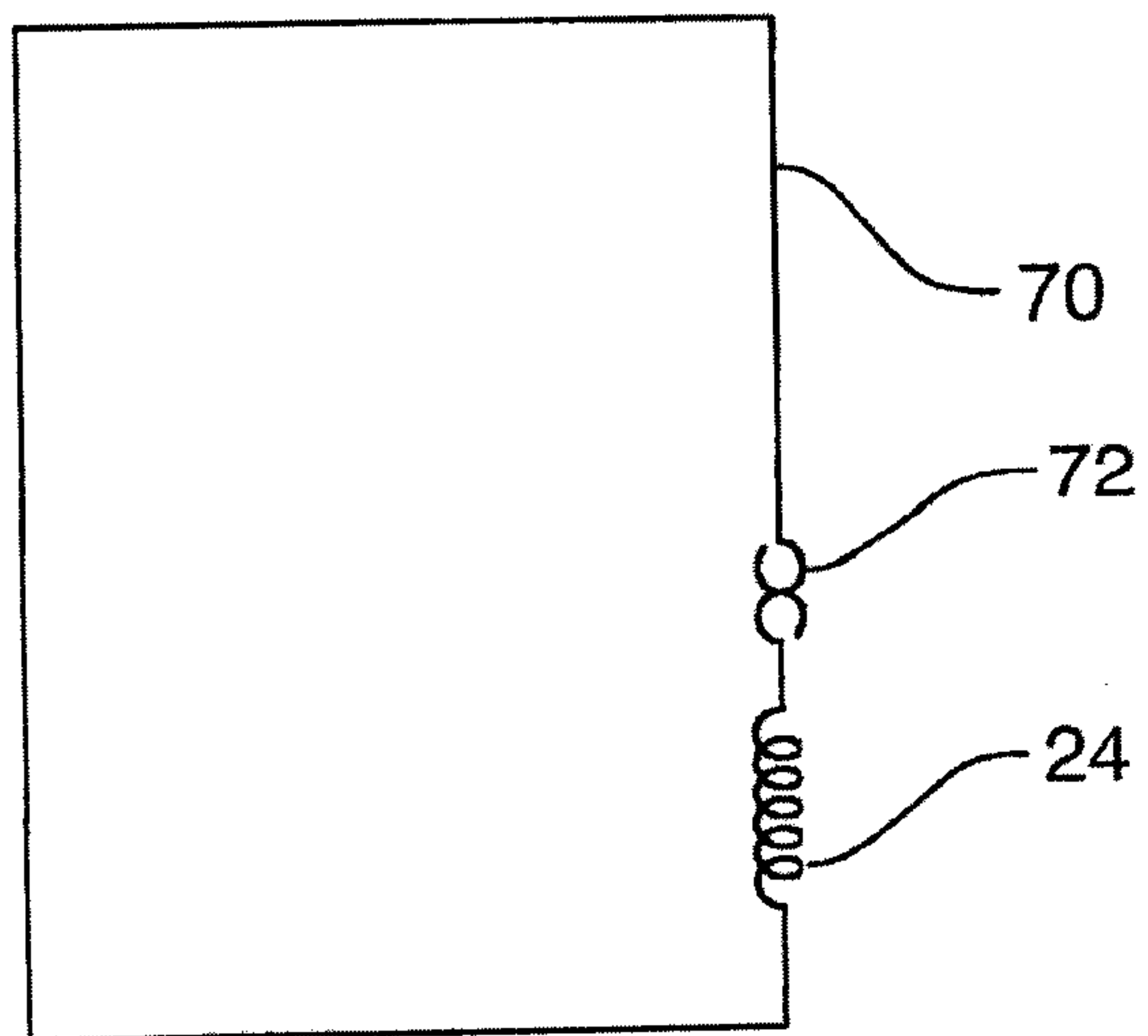


FIG.11B



25/29

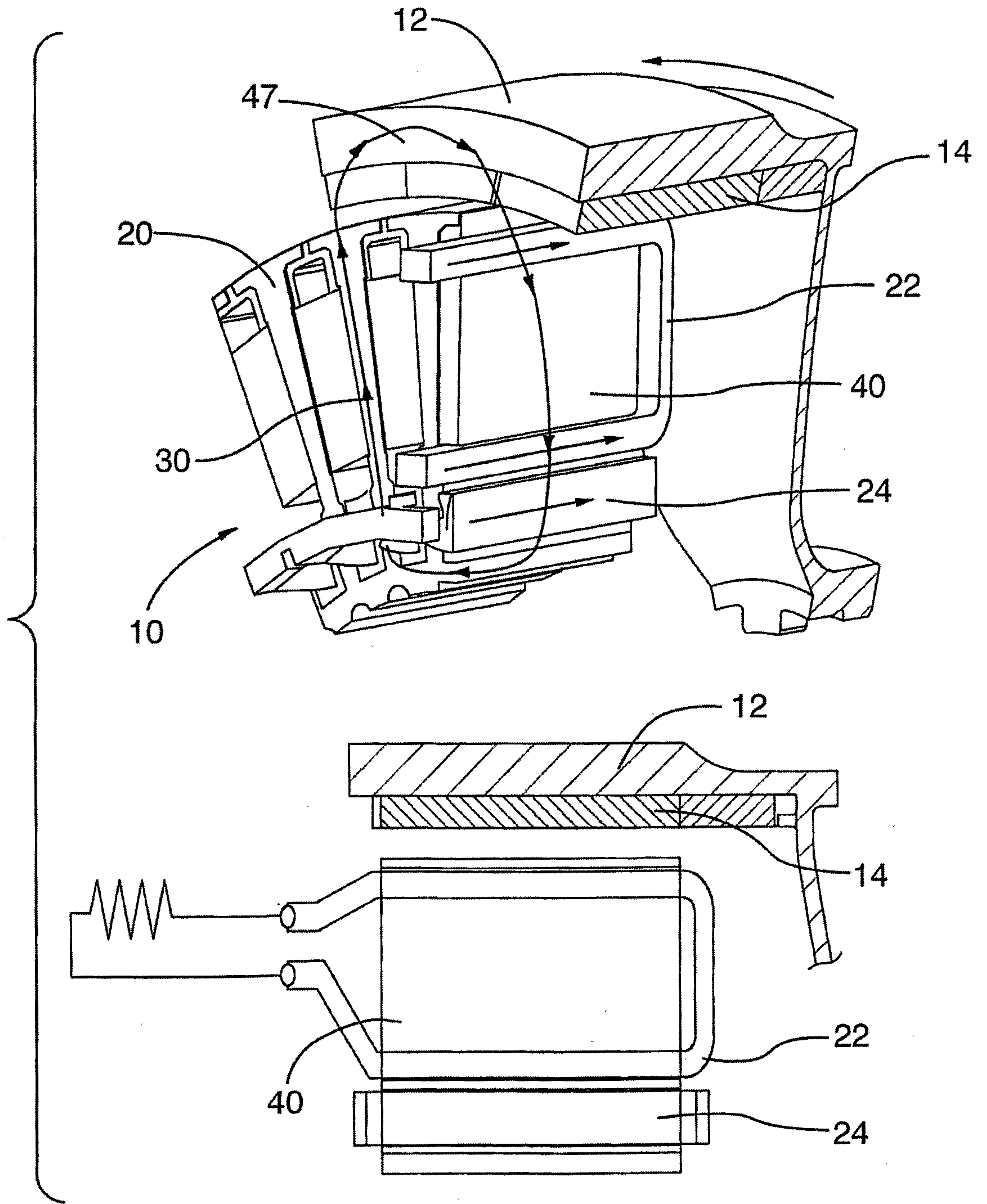


FIG.12A

26/29

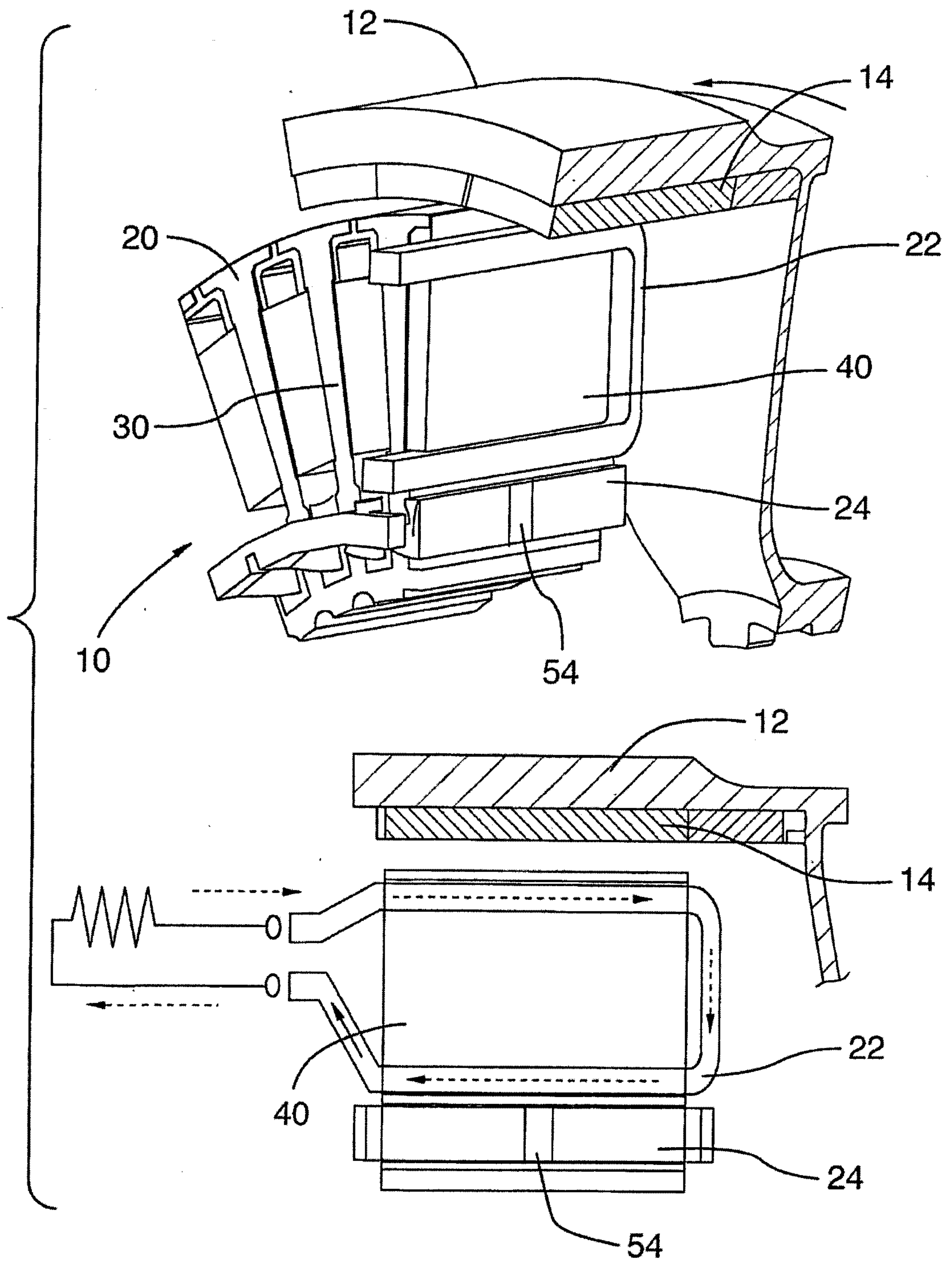


FIG.12B

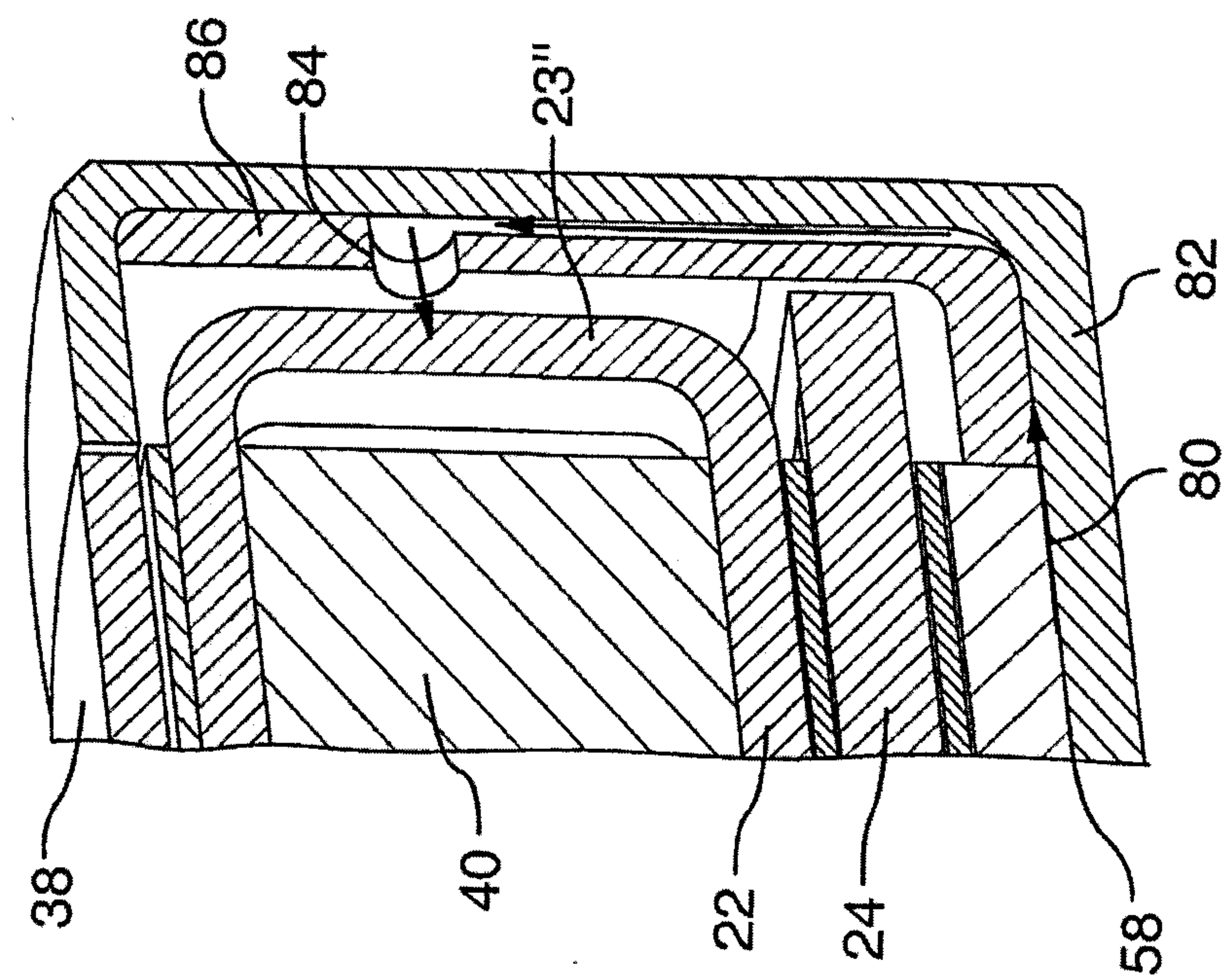


FIG. 13B

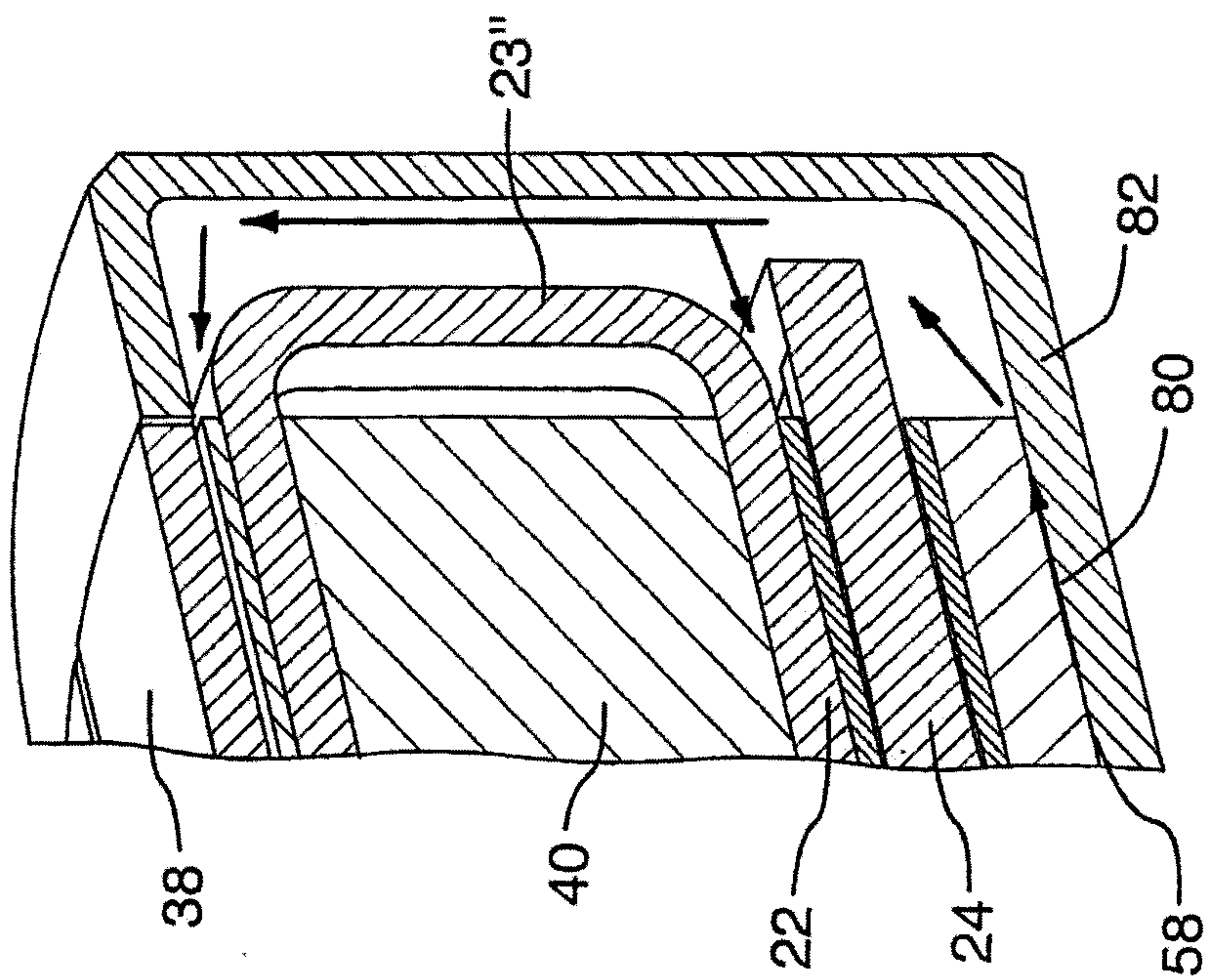


FIG. 13A

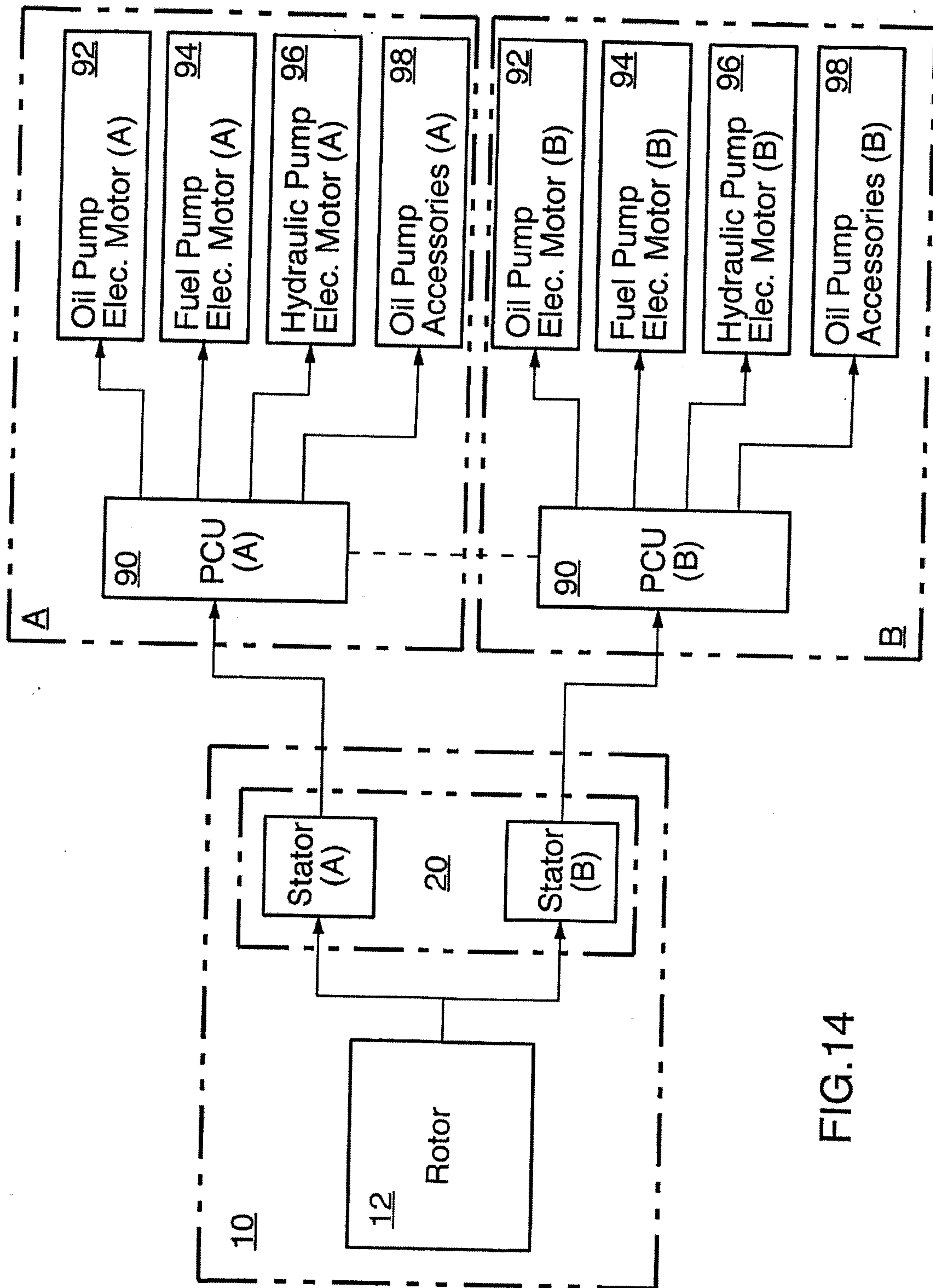


FIG.14

